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Recent Research on Wind Loading [and Discussion]

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Recent research on wind loading

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The paper reviews some of the research carried out over the past ten years into the effect of wind on vessel rolling and capsize. Two main techniques are discussed: the so-called discrete gust, where a vessel at its extreme windward roll angle is acted upon by a sudden increase in windspeed, and the stochastic approach, where the steady-state response to a random sequence of wind pulses is calculated. Some model experiments in a wind–wave tank are also described and compared.

1. Introduction

Although ship motion is usually associated with the effect of waves, it is often the additional effect of wind that determines whether or not the vessel will capsize, and it is therefore vital that studies of extreme behaviour of vessels properly take account of wind loading.

When a vessel is subjected to waves in a seaway, the most extreme behaviour will generally occur for waves on the beam; since the wind will usually be blowing in the direction of wave propagation, the wind will also generally be on the beam in this case, and the largest possible area of the vessel will be exposed to the wind. Wind blowing over unstreamlined shapes such as a vessel superstructure or hull in the beam direction will generate a pressure on the upstream faces roughly equal to the total pressure (static pressure + dynamic head), while separation of the flow from the downstream corners will induce a pressure lower than the static pressure on the downstream faces, due to the curvature of the streamlines enclosing the separation bubble. The end result is a considerable side force, but more importantly a large heeling moment about the roll centre, with fluctuating components at both the roll frequency and its harmonics, and at the frequencies of the turbulence components in the wind.

Considering first the mean component of the wind loading, this will cause the wave-induced rolling to occur about a line inclined to leeward, rather than vertical, so that the vessel will approach nearer to the capsizing or downflooding condition than it would in the absence of wind. In addition, any water shipped on deck at the extreme excursion increases this heeling moment on average, as it spends most of its time on the leeward side (see figure 1).

Dealing with the fluctuating components of wind loading is more problematical, and it is usual to make considerable simplifying assumptions in estimating their effect; in particular, the concept of a discrete gust, a sudden increase in wind speed from one steady value to another, resulting in an equivalent change in heeling moment, is often used. These approaches will be discussed in later sections.

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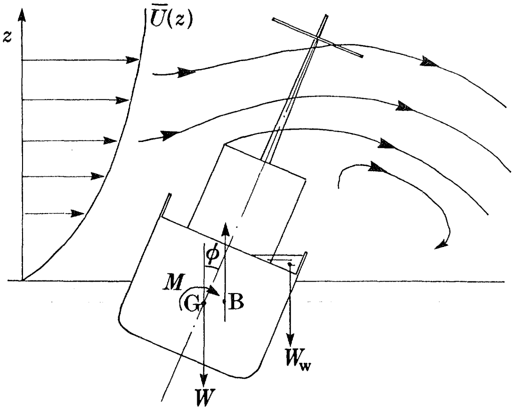
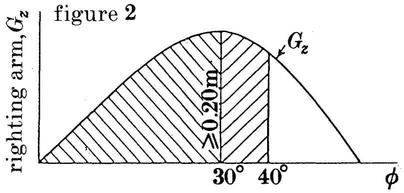


Figure 1. Vessel rolling due to wind loading.



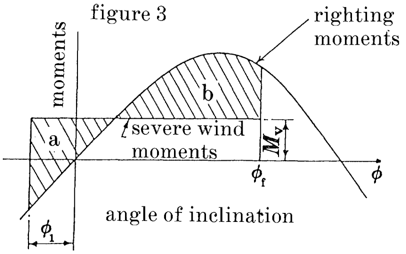


Figure 2. IMCO recommended stability criteria (for fishing vessels). (i) $\int_0^{30°} G_z \,\mathrm{d}\phi \geqslant 0.055$ m rad; (ii) $\int_0^{40°} G_z \,\mathrm{d}\phi \geqslant 0.090$ m rad; (iii) $\int_{30°}^{40°} G_z \,\mathrm{d}\phi \geqslant 0.030$ m rad; (iv) $G_{z30°} \geqslant 0.20$ m; (v) $G_{z\max}$ should occur at $\phi \geqslant 30°$, but no less than 25°; (vi) $G_{m_0} \geqslant 0.35$.

Figure 3. Weather criterion (IMO): the ratio, area 'b': area 'a' is not less than 1.

2. Stability criteria

The criteria for vessel stability adopted by national and international maritime organizations are typically of two types, in that they either allow a margin of stability to account for wind effects, or specifically include estimates of wind loading for the particular vessel type based on the windage area and other vessel characteristics.

The first approach is typified by the early IMCO criteria applied to fishing vessels (figure 2), developed from the original Rahola criterion (Rahola 1939). The stability of the vessel is represented by the variation of the righting arm G_z (ratio of righting moment to vessel mass) with angle of roll. G_z typically rises to 0.2 m for a roll angle ϕ of about 30° and then falls again to zero at the capsize angle. The shape of the curve and the value at 30° are intended to ensure that such small vessels are adequately stable in all likely conditions, but take no direct account of wind, and could result in capsize if the vessel were designed with a sufficiently large windage area.

The second approach is typified by the current IMO 'weather criterion', which starts by estimating a wind moment based on the vessel windage area and a highest mean wind speed, and combines this constant moment with the previous stability curve (figure 3). The estimated roll excursions are then assumed to occur symmetrically about a heel angle where the net moment is zero, yielding the maximum windward roll excursion ϕ_1. A worst case is now assumed where a sudden constant wind moment of 1.5 times the mean value is applied at the extreme windward excursion ϕ_1. The stability criterion requires that the positive area 'b' of the net righting moment up to the point of downflooding be larger than the negative area 'a'. In other words, the net integrated righting moment over the whole roll cycle must be stabilizing, so that if this worst condition persisted, the vessel would not reach the downflooding angle.

Although such a criterion is no guarantee that a vessel will not capsize or founder due to the combined action of wind and waves, it represents nevertheless a reasonable criterion against which to judge more sophisticated techniques based on the simulation of actual vessel behaviour.

3. Discrete gust models

We describe two recent dynamic models based on the response to a discrete gust, those of Odabasi & Vince (1982) and of Flower (1988). Both use a 'weather criterion' approach, where a vessel at its most vulnerable roll angle is subject to a sudden and sustained gust, and the behaviour analysed to see if the subsequent motion brings the vessel to a dangerous condition.

Odabasi & Vince pointed out that the common weather criterion takes no account of the beneficial effect of the vessel's natural roll damping in reducing the roll amplitude induced by the gust, and set about solving a model roll equation that included both linear and nonlinear damping terms. They also pointed out that the common weather criterion also assumes that wave action is inoperative during the gust. We shall return to this point later.

Odabasi & Vince use as their model equation

$$I_\phi \ddot{\phi} + (N_1 + N_2 \phi^2)\dot{\phi} + A\phi - B\phi^3 = M(t), \tag{1}$$

where I_ϕ is the moment of inertia in roll, N_1 and N_2 the linear and nonlinear damping coefficients, and A and B are chosen to give an approximation to the righting moment as a function of roll angle ϕ. $M(t)$ is the wind forcing moment, represented in their calculation by $M_g H(t)$, where M_g is the assumed constant wind moment and $H(t)$ the Heaviside unit function. Equation (1) is then solved approximately for the initial conditions of the weather criterion ($\phi(0) = \phi_1$, $\dot{\phi}(0) = 0$), using a modified Krylov & Bogoliubov (see Pipes 1958) method. The solution of equation (1) is found to be of the form

$$\phi(t) = \phi_s + a(t)\cos\theta(t) + \epsilon u_1(a, \theta), \tag{2}$$

where ϕ_s is the final settling heel angle after the motion has decayed, and a, θ and ϵu_1 are explicit functions of time and the various parameters in equation (1).

Odabasi & Vince plot the roll response against time for a typical stern trawler for various initial roll angles ϕ_1 and values of N_1, the linear damping coefficient. Their results are reproduced in figure 4 and table 1, and show that typical values of damping reduce the maximum roll angle by up to 8° for large initial roll angles.

More recently, Flower (1989) has solved both equation (1) and a related equation having a somewhat different form for the nonlinear damping coefficient by the Beecham & Titchener (1971) method, which is claimed to be simpler and to give generally more accurate results. Flower has also integrated the equations numerically for comparison. Flower's alternative model equation uses the modulus of the roll

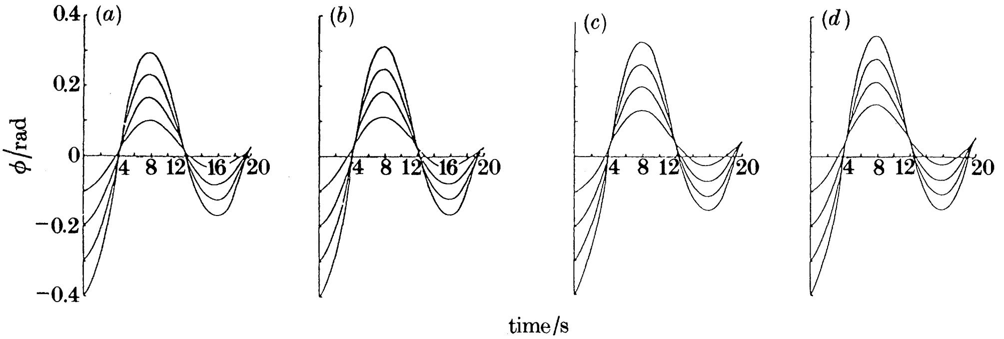


Figure 4. Effects of gust amplitude and initial angle on gust response. (*a*) $M_g = 198.6$; (*b*) $M_g = 297.9$; (*c*) $M_g = 397.2$; (*d*) $M_g = 496.5$. (From Odabasi & Vince 1982.)

Table 1

		ϕ_{m}/rad			
ϕ_0/rad	M_g :	198.6	297.9	397.2	496.5
−0.1		0.1376	0.1561	0.1760	0.1942
−0.2		0.2386	0.2564	0.2757	0.2949
−0.3		0.3380	0.3568	0.3770	0.3950
−0.4		0.4389	0.4571	0.4767	0.4962

angle rather than its square in the nonlinear damping term, but is otherwise similar to equation (1)

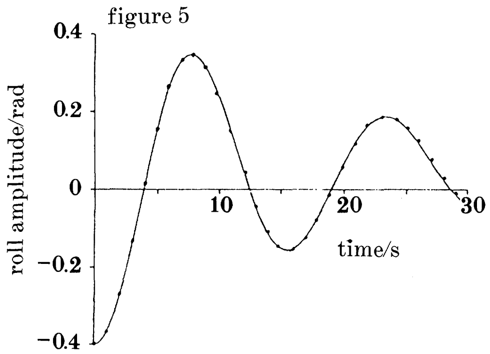
$$I_\phi \ddot{\phi} + (N_1 + N_2 |\phi|)\dot{\phi} + A\phi - B\phi^3 = M(t). \tag{3}$$

Flower's solution for equation (1) agrees with Odabasi & Vince within 10% on the maximum roll excursion, but to much higher accuracy with his fourth-order Runge–Kutta solution of the equation, and it seems that the method of Beecham & Titchener (1971), developed initially for dealing with aircraft flutter problems, is generally preferable. Flower's figures for his two equations are reproduced here as figures 5 and 6.

The discrete gust models appear more sophisticated than the weather criterion approach because they solve a reasonably accurate model of the vessel's motion, specifically including the hydrodynamic (and aerodynamic) damping in coefficient form. On the other hand, at least in the form given here, they do not include the direct wave action, and if one were to apply them to a zero-gust case, they would underestimate the roll excursion by comparison with the steady-state behaviour of a vessel in a uniform wave train. In one sense, the simple weather criterion compensates by allowing a steady-state response where the damping is balanced by the wave action, although the compensation is only implicit. There may be a case for including wave action in the discrete gust model, especially when the dominant wave encounter frequency is close to the vessel natural roll frequency.

4. Stochastic models

An alternative approach that avoids the artificiality of the worst-case weather criterion type of approach is developed in two papers on a stochastic model (Cardo & Michelacci 1982; Michelacci 1982). Here a simple model equation representing the



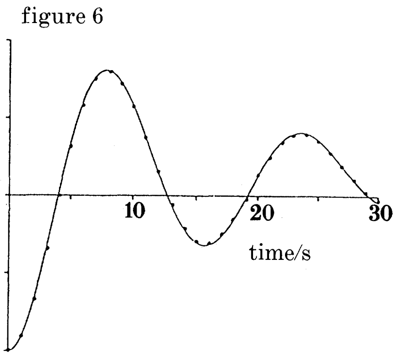
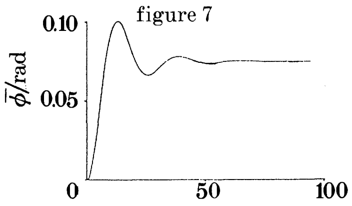
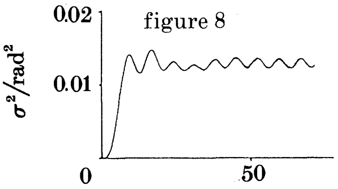


Figure 5. Calculated roll response obtained from integrating the equation of the form: $\ddot{\phi}+(n+m\phi^2)\dot{\phi}+A\phi+B\phi^3=F$. ——, Runge–Kutta solution; ……, approximate analytical solution. (From Flower 1989.)

Figure 6. Calculated roll response obtained from integrating the equation of the form: $\ddot{\phi}+(n+m|\phi|)\dot{\phi}+A\phi+B\phi^3=F$. ——, Runge–Kutta solution; ……, approximate analytical solution. (From Flower 1989.)





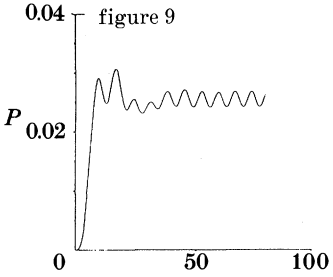


Figure 7. Predicted mean roll as a function of time. (From Michelacci 1982.)

Figure 8. Predicted variance of roll as a function of time. (From Michelacci 1982.)

Figure 9. Probability of capsize as a function of time. (From Michelacci 1982.)

vessel dynamics is driven by a forcing function representing regular wave action together with a random process representing the wind. The model equation is

$$I_{\phi}\ddot{\phi}+N_1\dot{\phi}+\Delta\overline{GM}\phi=E\cos(\omega t+\theta)+s(t). \tag{4}$$

Here only a linear damping coefficient N_1 has been used, and a linear righting moment $\Delta\overline{GM}\phi$. The forcing function consists of the sinusoidal wave action moment $E\cos(\omega t+\phi)$, plus the stochastic wind forcing function $s(t)$. In the slightly earlier paper (Cardo & Michelacci 1982), a fluctuating wind loading is represented by a randomly distributed sequence of Dirac delta functions $A\Sigma\delta(t-t_i)$, while in the second paper a decaying step function is used in place of the delta function.

By using the simple second-order linear differential response equation of equation (4), calculation of the mean and variance of the roll response as they evolve in time is comparatively straightforward for given vessel and forcing characteristics, shown diagrammatically in figures 7 and 8. In addition, the probability of the roll excursion exceeding a critical value at time t can also be calculated. This probability is just given by $P=\sigma^2(t)/(\phi_{\mathrm{cr}}-\bar{\phi}(t))^2$, where $\bar{\phi}$ and σ^2 are the mean and variance of the roll, and ϕ_{cr} the critical roll angle. This is shown in figure 9 for a critical roll angle of 45°.

Although the stochastic approach uses a more realistic forcing function than the discrete gust model, the response equation is unrealistic, especially for large roll

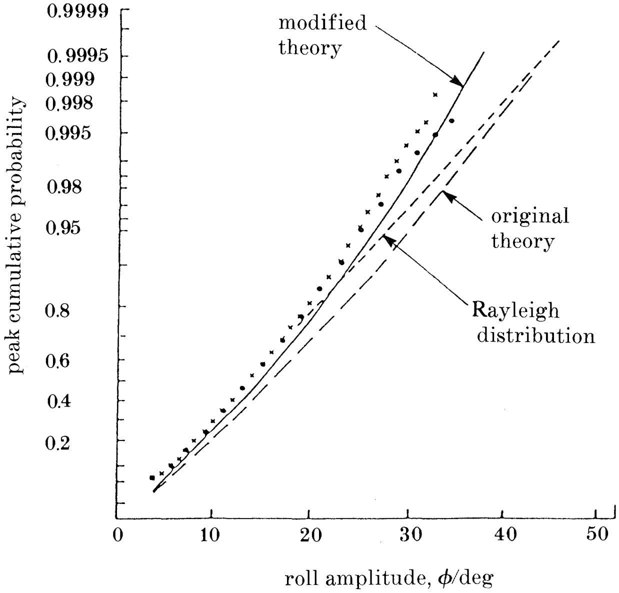


Figure 10. Cumulative probability of reaching roll amplitude ϕ. (From Roberts & Standing 1983.) ●, Peaks and troughs (averaged); ×, ranges.

angles. The worst aspect is the form of the righting moment, which cannot be considered linear above say 20°, and usually reaches a maximum at around 30°. The damping coefficient is also usually considered to be significantly nonlinear above say 30°. If these nonlinearities can be incorporated into the response calculation, then the stochastic model could be a very useful guide to vessel stability in realistic wind and waves.

Here we should mention the probabilistic model of Roberts (Roberts & Standing 1983), even though it has not yet been applied to wind forcing. The theory was developed in a series of papers to predict the statistical characteristics of roll (standard deviation of roll, or probability of roll angle exceedance, for instance) in a vessel subject to wave forcing of given spectrum.

The response is assumed to be a Markov process, driven by white noise filtered to have the assumed wave spectrum. The response equation can be nonlinear, and Roberts uses a form similar to equation (3) in much of his work. Figure 10 shows a typical comparison of the theory with model experiments in a wave tank. The results show the cumulative probability of the roll amplitude reaching particular values, and the deviation of both experiment and theory from a Rayleigh distribution is attributed to the ability of the theory to take account of nonlinearity in the damping coefficient. In Roberts & Standing (1983) the possibility of calculating roll response due to wind is discussed, and there would appear to be no particular difficulty in applying the method, using a typical wind spectrum, nor in combining both wave and wind forcing by this method, especially if the wave and wind fluctuations can be considered as uncorrelated.

Recently, a new approach to the prediction of capsize in waves has been under development (Thompson 1990). This approach demonstrates the appearance of chaotic behaviour in nonlinear systems such as ships rolling in waves, and shows how the 'stability basin' of a rolling vessel can be eroded by such behaviour, leading to

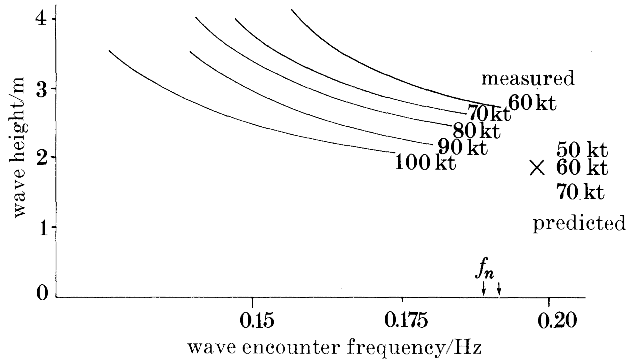


Figure 11. Comparison of measured and predicted capsize points.

a finite probability of capsize within the basin. The interest from the point of view of wind effects seems to be that models with a biased restoring function are more easily dealt with by this method, and that a mean wind is the most common source of bias.

5. Experimental studies

Experimental verification of predicted extreme behaviour are difficult to achieve, especially at full scale. Several years ago, an attempt was made at BMT (then NMI Limited) to compare a weather criterion prediction with observed capsize of a small model trawler in a wind and wave facility (Wills *et al.* 1984). The comparison achieved was not particularly close, but is summarized here for interest.

The predictions were made using the weather criterion model discussed in §2. The starting windward roll deflection was estimated from the Japanese weather criterion formula

$$\phi_1 = (138rs/N)^{\frac{1}{2}}, \tag{5}$$

where r is a wave-slope factor related to the vessel characteristics, s is an estimated maximum wave steepness and N is the roll damping coefficient, assumed to be 0.02. Other ways of estimating the roll starting angle might be more reliable. A gust moment of 1.64 times the steady wind speed was then assumed, based on wind gusts actually measured at sea (Wills 1989), and the capsize points for several windspeeds was estimated.

The model was released beam-on in regular wave trains of different encounter frequency and steepnesses, and in different windspeeds. Figure 11 summarizes the observed capsizing thresholds for different windspeeds as a function of wave steepness and encounter frequency, and includes the predicted capsize points calculated for three windspeeds. No great accuracy can be claimed for the experiments, but the match between prediction and experiment is reasonable when the wave encounter frequency is close to the vessel roll frequency.

Figure 12 shows a typical sequence of events leading to capsize, obtained by analysis of video recordings. In this particular case there was an 80 kt wind and wave encounter frequency of 0.88 of the vessel roll frequency. The extremes of roll are shown as a series of snapshots from right to left. At the start, the vessel is rolling from an upright position in the trough of the wave to 25° leeward at the wave crest. As the sequence progresses, the vessel is heeled to leeward even at the peak of its

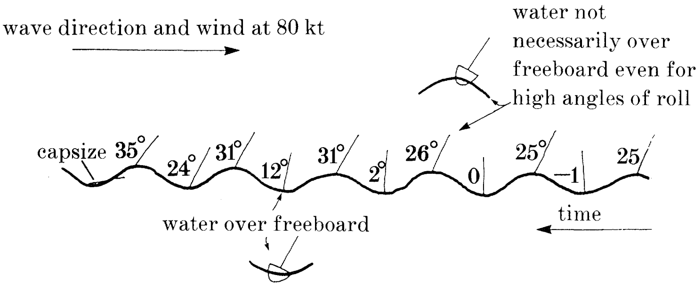


Figure 12. Roll behaviour leading to capsize. Wave encounter frequency is 0.167 Hz, $T_\theta/T_\omega = 0.88$.

windward roll, and begins to ship water over the leeward rail while lying in the trough of the wave. At the same time, the phase of the roll cycle is moving downwind, so that the lee rail is in the rising face of the next wave. Within two roll cycles the vessel has capsized.

6. Conclusions

It is difficult to draw firm conclusions in such an open area, but it seems fair to claim that the weather criterion is at least moderately successful in allowing for wind effects on ship motion. Discrete gust models need to allow for additional effects such as wave action and water on deck if they are to become more reliable than weather criterion methods for predicting extreme motion, as do stochastic models, which are still at an early stage. The approach of Roberts seems to hold the best hope at present, especially as it appears to allow the calculation of the statistical characteristics of the response to realistic representations of both waves and wind. For instance, it would be possible to predict the probability of the vessel's reaching a critical angle of roll within a specified time, for given wave and wind conditions, incorporating realistic wave and wind spectra, and allowing for realistic nonlinearities in both damping and righting moment such as those used in equation (3). The major remaining deficiency in representing the real situation may then be in ignoring the effects of water on deck at extreme roll angles. Perhaps it will be found possible to account for this in a comparatively simple manner through an additional nonlinear term.

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Discussion

B. R. Clayton (*University of Nottingham, U.K.*). During a research programme on the evaluation of wind-assisted ship propulsion it was found that motion damping played an important part in the technology (see Sinclair & Clayton 1988; Clayton & Sinclair 1989*a*, *b*). Indeed, previous studies of the subject concentrated on the thrust optimization of wind-assisted devices, such as aerofoils, wind turbines and boundary layer control cylinders. Nevertheless, in the work referenced, it has been shown that greater benefit in terms of fuel saving mechanisms can be obtained by maximizing the motion damping moments generated by the wind-assisted devices. This results in reduced hydrodynamic resistance of the hull, a more uniform wake and an element of aerodynamic thrust augmentation which offloads the propeller.

As part of the work it was shown that wind turbines, in particular, generated substantial damping moments in beam winds, and thus probably beam seas. Earlier work at the University of Glasgow (see Bose & Small 1985) used a wind turbine on a small sloop, although the device was used to drive a water propeller. It was noted that roll motion was reduced and similar behaviour was reported from a larger fishing boat fitted with an auxiliary sail (see Sinclair 1989). Finally, it would seem that even on a much larger cargo ship substantial fuel savings were obtained as a result of motion damping from the simple Japanese sail design (see Hamada 1985). It is therefore contended that the addition of sails, or possibly a wind turbine, could have accumulated benefits for ships and particularly fishing boats which include improved stability in beam seas. The addition of a properly deployed sea anchor could add further to the stability of a fishing boat.

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J. A. B. Wills. I believe the aerodynamic damping afforded by sails has been recognized since the end of the sail era, and the recent research by Dr Clayton and others has demonstrated the effectiveness of both sails and wind turbines in this respect. A quite small mizzen sail has also been found to be effective, even after allowing for the extra heeling moment due to the sail, but persuading vessel operators to make use of sails or turbines is probably another matter. I suspect the same to be true for sea anchors.

D. W. ROBINSON (*Lloyd's Register, London, U.K.*). Lloyd's Register may have some suitable data for further research in the area of wind and response. The data were collected while testing a prototype voyage data recorder for accident investigation purposes on a 100 m containership and contains continuous time histories of wind speed, direction and corresponding roll angles. Visual examination of such raw data does show a steady wind induced heel and transient variations which may also be wind induced.

In view of the fact that such monitoring is now relatively easy and inexpensive, can Dr Wills comment on its suitability for fundamental work on ship response to wind?

J. A. B. WILLS. There may be considerable interest in such data, as long as the variables are accurately measured. A perennial question in this area of research is verification at full scale, for which Mr Robinson's data could be extremely useful if a properly corrected relative wind speed signal is available from the records.

M. GREENHOW (*Brunel University, U.K.*). Is the effect of wind on capsize mainly due to it producing steeper and asymmetric incoming waves or are the wind-induced overturning moments significant? Can Dr Wills comment on the scaling of wind-induced moments and operation of freeing ports?

J. A. B. WILLS. I think there is no doubt that the direct wind-induced moment is very significant in capsize, as is recognized in the 'weather criterion' approach to stability. The additive effect of the steady wind-induced heel and the wave-induced roll oscillation brings the vessel to the point where significant water is shipped on deck at the leeward extreme of the oscillation, from which recovery becomes very difficult.

The model tests were carried out with correct Froude scaling of the wind speed, although of course not at correct Reynolds number scaling, which would require a full-scale test model. However, in wind tunnel experiments it is generally considered that Reynolds number effects are slight for bluff, sharp-edged shapes such as those typical of ships' superstructure, because the flow separations that dominate the flow and spring from the corners of such shapes are practically independent of Reynolds number. For freeing ports, some variations in discharge coefficient between model and full scale were expected, and allowance was made for this in determining the area of the ports at model scale.

A. INCECIK (*University of Glasgow, U.K.*). As the effect of waves on the wind velocity field gives rise to oscillations in wind forces these dynamic load effects may excite motions of a floating vessel at its natural roll frequency. Has Dr Wills carried out any measurements to investigate such phenomenon in his unique combined wave-wind tank?

J. A. B. Wills. In practice it is difficult to distinguish between wind-induced and wave-induced motions at the wave-encounter frequency, because they are both phase locked to the same forcing signal. We have in the past measured the instantaneous wind velocity components over regular waves in the wind–wave facility, yielding ensemble average wind fields that would add to the wave-induced motions. Unfortunately, commercial pressures have since forced us to demolish the facility, so that further work in this area is unlikely to be carried out at BMT. There are, however, a number of both smaller and larger facilities of this type around the world in which such work could be carried out.

A. Francescutto (*University of Trieste, Italy*). It is clear that fully linear models are inadequate for the description of extreme phenomena such as capsizing, irrespective of how good the description of the wind action is. On the other hand, most of the nonlinear approaches quoted, assuming a continuous dependence of the solution on the parameters, appear now completely appropriate. An important feature of nonlinear rolling is the possibility of bifurcations in particular ranges of frequency, both in deterministic and in narrow-band stochastic beam sea (Francescutto 1990). As a consequence, jumps in the amplitude of the oscillation between antiresonant and resonant or subharmonic states is possible for small changes of some parameter or the action of some perturbation, such as water on deck, shifting of cargo or gusts of wind. Since this brings about large-amplitude rolling and complicated transients, I would stress the importance of an analysis of the effect of wind on rolling amplitude bifurcations.

J. A. B. Wills. I am grateful to Professor Francescutto for his remarks on the inadequacy of the analytical approaches discussed, although I think they will be the only ones familiar to most people. The only mention in the written version of the paper of the chaos theory approach is the recent work of Thompson (1990), presented at the same preceding meeting as Professor Francescutto's paper, and which I unfortunately did not attend. The indications are that study of bifurcations in the nonlinear solutions will lead to exciting and relevant results.

G. Victory (*Surrey, U.K.*). In the video recording of a model trawler in combined wind and wave conditions, the vessel finally capsized. The amount of water remaining on the deck was clearly a contributory factor, which makes one question the adequacy of the normal freeing ports in bulwarks for 'rapidly clearing the weather deck in all weather conditions.' If not, then a greater percentage area of open rails should be specified.

It seems also that the water is usually assumed to be static, whereas in real storms it is very dynamic, and when surging on deck can be trapped by deck erections and result in high inertial forces and a much greater quantity being retained on deck than a static study would suggest. Perhaps this could account for the much publicized loss of the *Gaul*, a Hull stern trawler, which, despite going to a DOT Formal Investigation, was never explained.

To protect the crew dealing with the catch behind the high bridge structure, the bulwarks were carried forward and swept up to the bridge level in a wide arc to provide a sheltered zone. Normally water could not accumulate above the freeing port level if it had time to escape. But if the vessel was pooped by a sea running up to the sloping afterdeck, the dynamics of the wave would permit it to pile up in this space aft of the bridge and hang there for some moments. This extra weight plus the inertial forces could produce a much greater overturning moment and capsize the vessel, a condition which would not have been disclosed by a static approach. Would Dr Wills consider that the present state of affairs could be improved to reduce the additional overturning moment.

J. A. B. WILLS. I find Mr Victory's comments particularly interesting, because it appeared very clear in the model experiments that water retained on deck made a very large contribution to the probability of capsize, and this point is made in the written version of the paper. The freeing ports on the model were sized, according to DOT recommendations, with allowance for model scale effects, but the time taken to clear the deck of water prevented full recovery from each inrush, with the consequence that roll occurred about progressively larger and larger heel angles, as seen in the video. No doubt replacement of the bulwarks by rails would improve this particular situation, but I believe is not very popular with seafarers.

Additional reference

Francescutto, A. 1990 On the nonlinear motions of ships and structures in waves. *Proc. IUTAM, London, June 1990.*