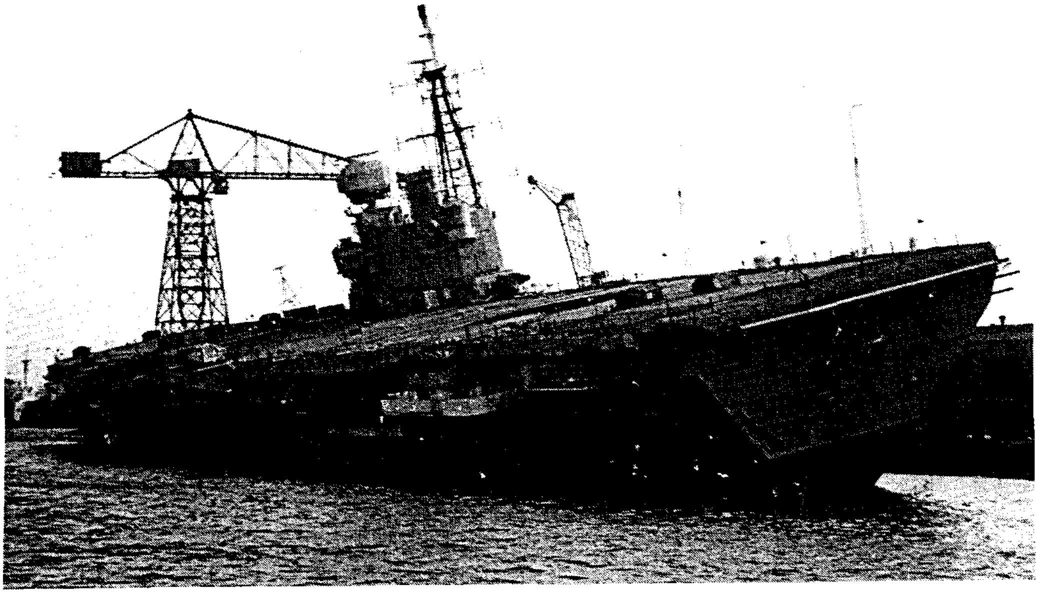

Fig. 1—Ships must survive and work when heeled: H.M.S. 'Hermes' on trials at 8°

CAPSIZE AND STABILITY

BY

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Introduction

Capsize of an undamaged warship is happily a very rare event. The last major incident in the Royal Navy was the loss of H.M.S. *Captain* in 1871; the Japanese lost *Tomoruzu* in 1934, while the U. S. Navy lost *Warrington* early in 1944 and *Hull*, *Monaghan* and *Spence* later that year. Capsize of merchant ships, particularly the smaller ones, is of more frequent occurence.

Stability is the term used by naval architects to measure the ability of a ship to return to the upright position when heeled by external forces such as wind and waves or by internal forces due to shift of weights. This article will concentrate on the criteria for stability which are intended to ensure that an intact warship will not capsize in normal operation. Some consideration will also be given to the effect of damage on stabiltiy.

Righting moments

The righting moment (Fig. 2), which will restore a ship to the upright, is the product of the weight (W) of the ship and the separation of the lines of action of weight and buoyancy (GZ). For small angles of heel the metacentre M is defined as the intersection of the upright and heeled lines of the buoyancy force for which $GZ = GM \sin \theta$. This approximation becomes less and less accurate for angles of heel greater than 10° and cannot be used in considering capsize—which should only occur at much greater angles of heel. The movement of the centre of buoyancy as a ship heels depends on the changing shape of the immersed portion of the hull and there is no simple expression for the curve of righting levers (GZ) in terms of θ.

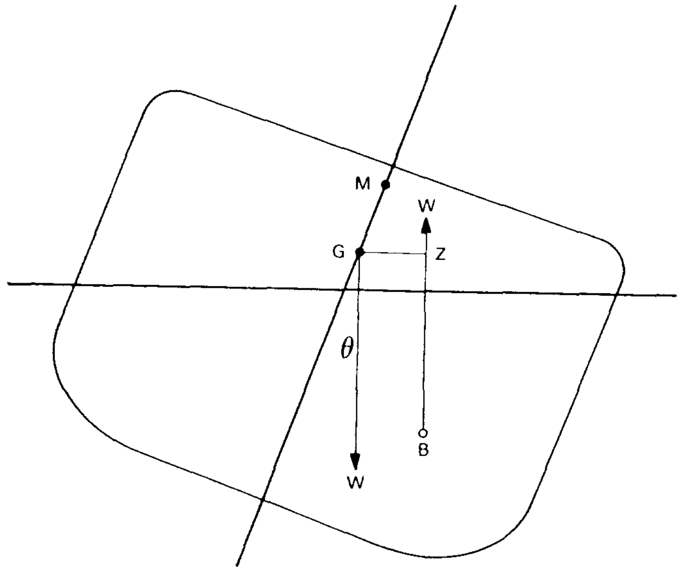

FIG. 2—RIGHTING MOMENT

Dynamic Analysis

If capsize occurs it will almost inevitably be when the ship is moving violently in a rough sea. The overall motion of a ship in a seaway has six degrees of freedom which are usually described in the following form:

angular:	roll	yaw	pitch
linear:	heave	sway	surge

The motion in each case may be defined by a second order differential equation of the form given below for roll. The six equations are coupled and, particularly in the case of broaching, the coupling may be significant.

$$I\ddot{\theta} + Bf(\dot{\theta}) + \Delta.GZ = F(t) \qquad (1)$$

where θ: angle of heel
t : time
other symbols are explained below

A full mathematical solution of such coupled second order equations is not possible for real cases. Furthermore, though the terms in equation 1 may seem familiar, their true signigicance is complicated. I is the polar moment of inertia in roll, not just of the ship but also of the water set into motion by the ship. The fluid velocities are non-uniform, time-dependent and random. Similarly, Δ is the mass of the ship and entrained water. Damping is represented by a coefficient B and a damping term dependent on some power of velocity. The restoring force GZ is a very complicated non-linear parameter derived from ship geometry. Finally, the forcing function F is a random function of sea state, time, previous history of the motion, etc.

Attempts are being made in all parts of the world to manipulate these equations into forms which lead to meaningful statements on ship safety. These approaches include decoupling the equation or using linear expressions for some of the terms. While these simple forms cannot say when capsize will occur, they may indicate that dangerous conditions are approaching.

Another interesting approach is to use methods which indicate zones in which stable (in the mathematical sense) solutions exist even if the solutions cannot be found (Lyapunov functions).

While it is unlikely that any of these approaches will lead to a sufficiently complete mathematical model of capsize, they are already increasing understanding of some of the mechanisms involved. For example, it is clear that the risk of capsize in some modes is reduced if roll damping is increased and it should be possible to establish criteria for roll damping.

However, it has to be remembered that a real ship is not the mathematician's idealized solid body. Capsize will usually be associated with some degree of flooding through a damaged door or hatch or with water trapped on deck. For all these reasons, mathematical and practical, naval architects are forced into the use of empirical quasi-static methods of assessing stability. There is full scale evidence, outlined later, which shows that the traditional representation of stability characteristics by use of the GZ curve is a very good mirror of reality.

Heeling Forces

Action of Wind and Waves

Beam winds will cause the ship to heel, the steady condition being calculated simply by summing the wind moments on each part of the ship given by the static pressure and its lever about the centre of lateral resistance of the immersed hull. The moment is calculated for the upright condition and varied as $\cos^2 \theta$ as the ship heels. Quite recently, wind tunnel tests have been carried out on a model of a frigate to confirm the accuracy of this approach for modern ships.

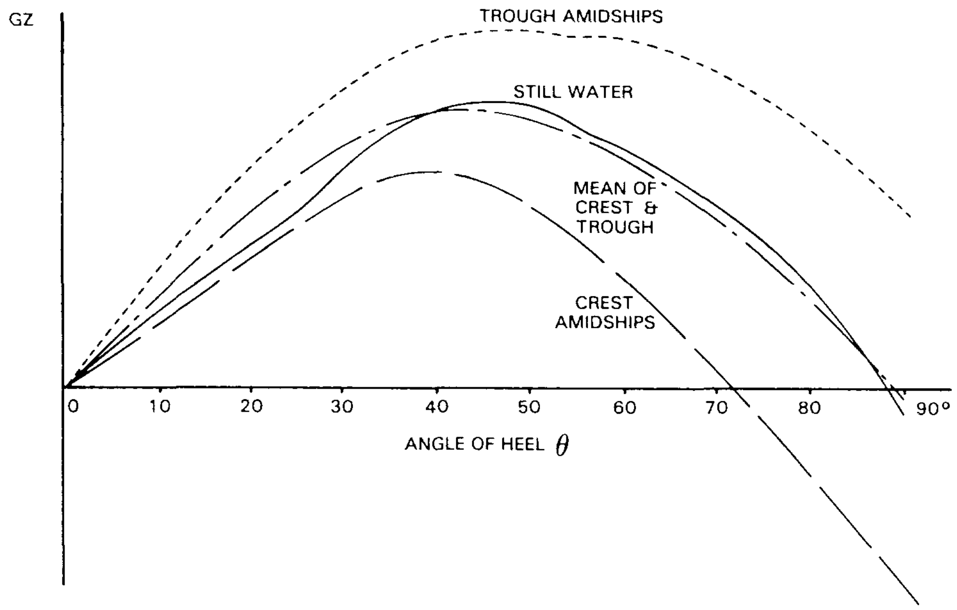

FIG. 3—GZ CURVES IN WAVES

The action of waves can affect the transverse stability of a ship in various ways (FIG. 3). The passage of wave crests along the length of the ship will cause a redistribution of buoyancy forces and it is found that the righting moment in roll will be reduced if the wave crest is amidships and increased if the crests are at bow and stern due to the added buoyancy from flare at the ends compared to the relatively wall-sided hull amidships.

If the wave encounter period is resonant with the ship's roll period the changing buoyancy can set up a heavy rolling motion which in an insufficiently stable ship might lead to capsize. Such a mode of capsize can only occur if the ship has a small metacentric height and little roll damping, and is unlikely in warships.

Beam seas are the most usual cause of heavy rolling which will be most severe when the wave encounter period coincides with that of the natural roll. Particularly when combined with a steady angle of heel from a beam wind, this condition can be very dangerous and was the mode in which the four U.S. destroyers were lost.

Broaching is another wave-induced motion which can lead to capsize. It occurs in following seas when a wave very slowly overtakes the ship. The geometry of the wave surface and the orbital velocities of the particles forming the wave combine to reduce the effectiveness of the rudder, steering control is lost and the ship swings violently down the face of the wave, ending broadside to the sea in the trough. The dynamic heeling force of the turn combines with the wave action to cause very large heel angles which have capsized many small ships. Broaching has occurred in frigates and must be very frightening but is unlikely to be a cause of loss in a large ship. Broaching can be prevented if critical combinations of course and speed are avoided but operational constraints may force the acceptance of risks.

Shift of Weights

The other types of heeling moment applied to a ship mainly involve a shift of weights. A heavy load may be hoisted over the side, fuel pumped from one tank to another, or the passengers crowded to one side. The ship can also be heeled by the centrifugal forces in a high speed turn.

Loll

If the centre of gravity is above the metacentre in the upright condition the ship is unstable and will heel—or 'loll'—until an equilibrium angle is reached. The loll can be either to port or starboard but in practice the inevitable small asymetric heeling moment will bias the loll to one side or the other. The lolled position is stable, the positive GM in this condition being numerically twice the negative value when upright.

Attempts to reduce the angle of loll by moving weights across the ship or counterflooding can be very dangerous. Such action will cause the ship to heel violently the other way to a greater angle of loll. The corrective action is to get rid of any free surface and to lower the centre of gravity by jettisoning top weight, and draining down. In warships, loll is only likely to occur after extensive damage and any heel in this condition is most likely to be loll rather than list. In particular, relatively small amounts of water can provide sufficient free surface to have a major effect with the ship upright. As soon as the ship heels, the free surface is much reduced.

Disasters

Since capsize is so rare, the few tragedies which do occur are studied with great care. On 17 December 1944 the U.S. Navy lost three destroyers, *Hull*, *Monaghan* and *Spence*, in a typhoon, with serious damage to other ships and the death of 790 men. During the morning the wind speed was measured on the flight deck of a carrier at 73 knots gusting to over 100 knots. *Hull* and *Monaghan* were about 10 years old, in good condition and with 70 to 75% fuel remaining. They found themselves beam on to wind, in the trough of the sea and unable to steer out of this condition. Just after midday the wind increased to 110 knots and, after 2 or 3 rolls to 70°, *Hull* was blown on to her beam ends and foundered by flooding down the funnels and boiler room inlets. *Monaghan* went in much the same way[1].

Spence was a larger and more modern ship but she was due to refuel and her tanks were only 15% full; ballasting was left too late. She rolled heavily to port, recovered, rolled again more heavily, and sank. Other ships came very close to disaster but survived. *Dewey*, a sister of *Hull*, was rolling to 75° when her forward funnel fell overboard reducing windage and top weight, which saved her.

This disaster led the Americans to carry out a major investigation into warship stability. It was at once clear that there was a very marked difference in the character of the GZ curves of the ships which were lost, or nearly lost, and those which survived. The survivors had a higher maximum righting lever and a greater range of stability.

The loss of *Tomoruzu* provided fewer useful lessons. She was over-armed, with a high centre of gravity and a lot of wind area. In a storm she just blew over.

In recent years, the loss of some 200 to 250 merchant ships is reported annually, about one-third of these occurring in the English Channel, North Sea, and Bay of Biscay. About 30 of these founder or capsize. Only in a few cases have full investigations been carried out and these all point to spread of flooding, a poor and early maximum value of GZ and an inadequate range of stability. It is, however, important to realize that U.K. waters are not necessarily safe; wind and waves can occur off the Lizard virtually as severe as those off Iceland though, perhaps, these conditions occur less often.

Stability Criteria

The American investigations led to a set of criteria for the stability of warships which were published by Sarchin and Goldberg[2]. These criteria, slightly modified, are now accepted by the R.N. and many NATO navies. The main criteria which apply to the undamaged ship relate to:

(*a*) Beam winds combined with rolling.
(*b*) Lifting of heavy weights over the side.
(*c*) Crowding of passengers to one side.
(*d*) High speed turning.

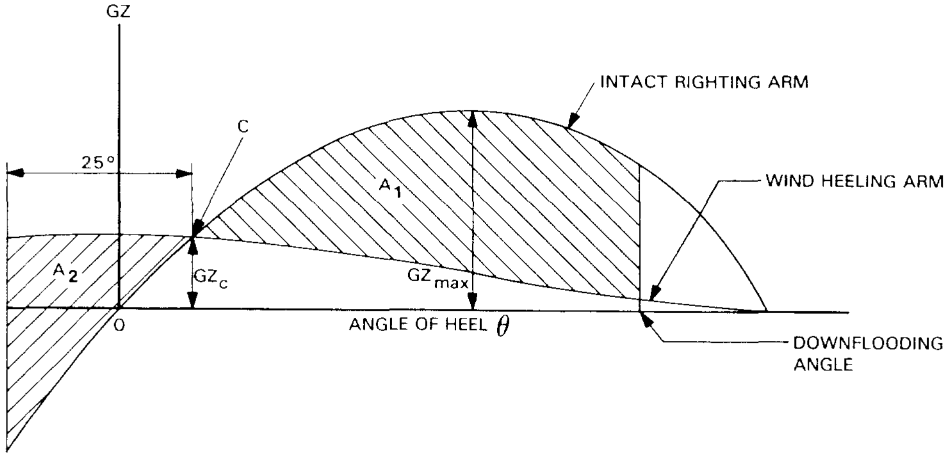

FIG. 4—GZ CURVE FOR BEAM WINDS COMBINED WITH ROLLING

The most critical case for warships is generally with wind and waves on the beam, and the two effects must be considered together since waves will always occur when high winds blow. If waves were not present the ship would only need sufficient righting moment to resist the heeling moment of the wind acting on the exposed area of the ship. To overcome the added effect of wave-induced rolling requires additional dynamic stability. Major R.N. vessels are designed to resist a nominal 90 knot wind measured at 10 metres above the water surface, the wind speed varying with height due to drag at the surface level. The force on exposed portions of the ship is given by

$$\delta F = 0{\cdot}0195\ V^2 A \cos^2 \theta$$

A in metres; V in knots; δF in Kgf

The heeling moment is then summed for all such areas and plotted as a heeling arm (= moment/displacement) superimposed on the GZ curve, as in FIG. 4.

The criteria which must be satisfied are as follows:

(*a*) The heeling arm at the intersection with the righting arm (GZ_c) should not be less than 60% of the maximum righting arm.

(*b*) The steady angle of heel should not exceed 30°.

(*c*) The area under the GZ curve represents the energy to resist rolling. The area A2 in FIG. 4 represents the energy put into the ship by a roll starting at 25° to windward and this energy must be counterbalanced by the area A1. The criterion is $A1 \nless 1{\cdot}4\ A_2$.

These criteria allow a margin for gusts, peak rolls and for uncertainties in the calculation.

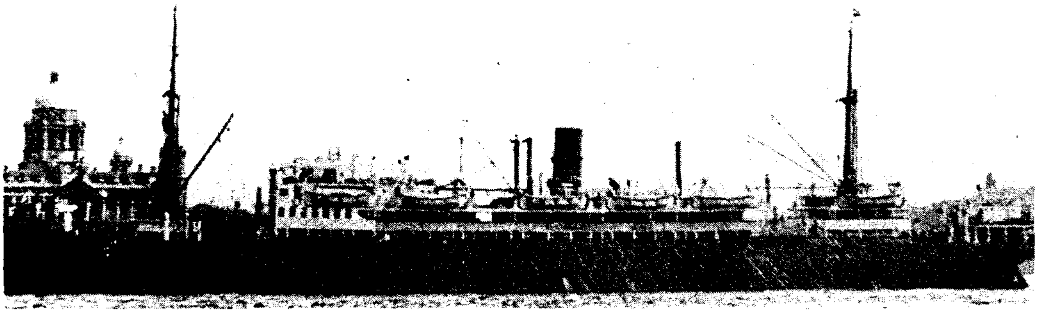

FIG. 5—'ABA' AT LIVERPOOL SOME TIME BEFORE 1940

FIG. 6—'ABA' LYING ON HER SIDE IN BIDSTON DOCK, BIRKENHEAD IN 1947

The lifting of heavy weights is not usually a critical condition for warships though it can be for auxiliary vessels. Once the weight is lifted off the deck its effective point of action is the point from which it is suspended so there is a rise in the centre of gravity (cg) as well as a lateral shift. Failure to recognize this point caused the loss of a merchant ship, *Aba*, at Birkenhead soon after World War II (FIGS. 5 & 6). The main engine was lifted using a purchase from the deck beams and the rise of the cg caused her to loll and capsize.

The heeling moment is calculated and compared with the righting moment, corrected for the rise of the cg. The ship is considered safe when the following conditions are met (referring to Fig. 7):

(*a*) the steady angle of heel θ_c does not exceed 15° (or the maximum operating angle of the crane);

(*b*) the heeling arm at θ_c, GZ_c, is not more than 60% of the maximum righting level, GZ;

(*c*) the reserve area A above the heeling arm curve is not less than 40% of the total area under the GZ curve.

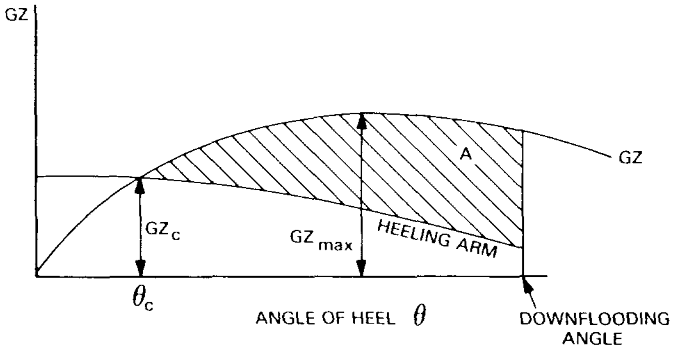

Fig. 7—GZ curve: effect of moving weights

Crowding of passengers to one side is dealt with in much the same way. It is assumed that they are packed close, 5 men per metre^2 with their effective cg at knee height. The heeling levers are superimposed on the GZ curve, as above, and similar criteria must be met.

The heel on turning is produced by the centrifugal force acting through the ship's centre of gravity times the lever from the cg to the centre of lateral resistance (roughly half draught). Such a calculation is very approximate but quite sufficient to show if a real problem exists. Again, the deduced angle of heel, righting arm and reserve area under the curve have to meet certain values.

To these basic criteria MOD has added some others to ensure that the angle of heel under small forces (wind, etc.) is not too great. These are aimed at efficient operation rather than safety.

Comparison of criteria

These criteria would seem to form an adequate guarantee that the ship meeting them is safe in normal operation but it is sometimes suggested that they are too demanding. Certainly, many ships of both the R.N. and U.S.N. operated in World War II in very bad weather without sinking, despite stability characteristics much inferior to those outlined.

A contract was placed with Yarrow Shipbuilders a few years ago to compare MOD standards with those of other navies and those of IMCO (now IMO) for merchant ships. The only set of warship criteria which was significantly different from those of the U.K. was the set used by Germany. Their criteria allow for the change of stability caused by transverse waves discussed earlier, perhaps rather strangely in association with a beam wind. The impact of the German approach on design and operation was found to be very similar to that of U.K. standards.

Both sets of naval criteria were more stringent that those required for merchant ships. Warships may have to operate in bad weather at high speed and on an unfavourable course; on the other hand, it can be argued that losses of merchant ships are too frequent. What is the acceptable loss rate of frigates?

Icing

The stability of a ship can be reduced in various ways, one of which is by the formation of ice on the upperworks. The rate at which ice forms is very variable and will differ from one part of the ship to another. As a convenient assumption MOD consider a uniform thickness of 150 mm on all horizontal surfaces. Icing and high winds are likely to occur together but if the ship were designed to withstand 90 knots winds when covered in ice it would be unacceptably stiff in normal operation, leading to violent rolling (see FIG. 8). Hence the criteria for wind loading discussed earlier are to be met at 70% of the maximum wind speed (i.e. 63 knots).

Icing can cause a very rapid and dangerous reduction in stability. Precautions are well described in *The Admiralty Manual of Seamanship* (BR 67(1) chapter 17), and this advice should always be followed when icing occurs. In brief, get rid of the ice and observe liquid loading restrictions.

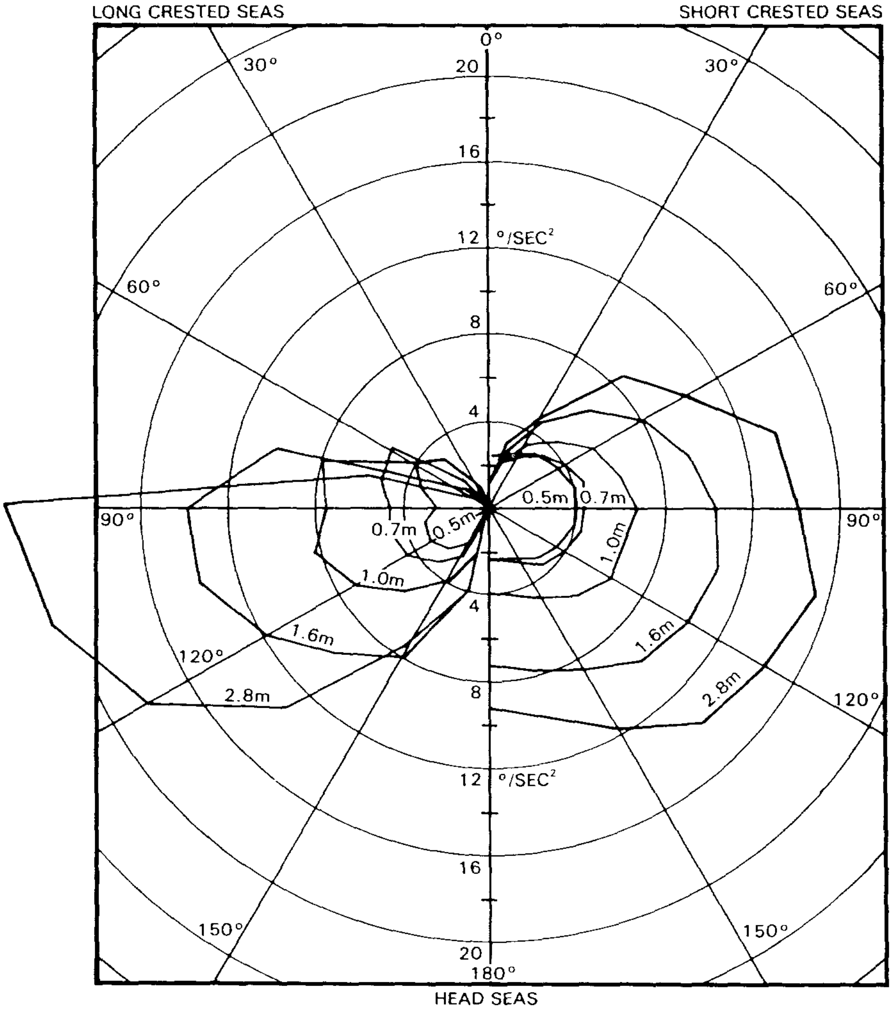

FIG. 8—EFFECT OF GM ON SIGNIFICANT ROLL ACCELERATION: SEA STATE 6, 15 KNOTS, UNSTABILIZED, ITTC SPECTRA

Damage

The survival of a ship following action damage depends on many factors of which flooding and its effect on stability is only one. The complete subject is too complex to be dealt with in this article and only those aspects most affecting stability will be considered.

Underwater damage will cause flooding and loss of buoyancy; for most forms there will also be a loss of stability. If the flooding is not symmetrical about the centre line there will be a heeling moment which is particularly dangerous when it acts on a ship whose overall stability has been reduced.

The ability of a ship to survive extensive underwater damage depends on:

(*a*) the initial transverse and longitudinal stability;

(*b*) reserve of buoyancy, that is the volume of watertight hull which is normally above the waterline;

(*c*) the extent of the damage and the extent to which it can be limited by:

  (*i*) watertight subdivision;

  (*ii*) stopping the spread of flooding by sealing slow leaks;

  (*iii*) effective damage control.

Major warships (over 92 metres in length) are required to withstand damage which will render a length of 21 metres (or 15% of the length, whichever is greater) non-watertight. It is assumed that all decks in this area are made non-watertight and that the transverse extent is either the full beam or any lesser distance giving a worse situation. The 21 metre length is roughly that expected from a World War II contact torpedo but is now best seen as an arbitrary value, with the increase of damage length with ship size reflecting an intuitive feeling that a big ship should absorb more damage than a small one.

After such damage the following criteria must be met:

(*a*) the angle of list or loll must not exceed 20°;

(*b*) the area between the GZ curve and the wind heeling moment up to 45° (or the angle at which unrestricted flooding can take place) must be in excess of certain values depending on the size of the ship. The wind speed used is much less, about 30 knots for a frigate. The usual criteria that

$$GZ_c \nless 60\% \, GZ_{max}$$
$$A1 \nless 1{\cdot}4 \, A2$$

must be met at that wind speed. These criteria are very similar to those of other major NATO navies.

For smaller warships and RFAs the size of the damaged zone to be withstood is reduced. More serious difficulties arise in setting acceptable standards for Ships Taken Up From Trade (STUFT) since very few merchant ships are designed to resist any flooding at all. Only passenger ships have any such requirement and even these meet a much lower standard than warships. After CORPORATE, this problem was discussed with the Defence Scientific Advisory Council (DSAC) Hull Committee, whose members include eminent designers of merchant ships. Their recommendations, since endorsed by the Marine Technology Board, are as follows:

(*a*) Troop-ships. Military personnel and their dependants should not be carried in ships which cannot remain afloat and stable with any two main compartments flooded.

(*b*) Every effort shall be made to ensure that ships employed, which satisfy (*a*), shall sink upright in the event of more serious damage.

(*c*) Where possible bulkheads shall be extended to ensure that water does not spread to undamaged compartments above the normal bulkhead deck.

(*d*) Merchant ships used as auxiliary warships shall meet full warship standards.

In particular, RoRo ships will have difficulty in meeting (*a*) with the vehicle deck flooded. The changes needed are not usually great; during CORPORATE *Rangatira* had an extra bulkhead fitted in about a week. It is possible to have special arrangements which permit an extra bulkhead to be bolted in place in about 24 hours.

The 'after damage' criteria have to be met even if there is asymmetric flooding. Longitudinal watertight subdivision is avoided as far as possible so that the ship's staff do not have to take any action after damage to prevent large heel angles. In some ships this requirement is satisfied by fitting automatic cross-flooding pipes. However, partitions which are not strictly watertight (e.g. cold and cool room doors) can hold up a head of water for a considerable time and with a ship where stability is low after damage this can cause considerable heel. Since CORPORATE some such semi-watertight partitions have been modified.

Design

New warships are always designed to meet all stability criteria throughout their life, with something in hand. This aim is not easy to satisfy for a number of reasons. In most cases the new class will be intended to carry novel weapons and other systems which themselves are not fully developed and, inevitably, these systems will grow in weight—usually high in the ship. The pace of technology is such that additional military equipment will be required even before the ship is complete and certainly during the life of the class. Finally, there will be insidious and unplanned weight growth during life, discussed later.

The design must allow margins on weight and height of the centre of gravity to allow for these additions and for any inaccuracies in the design process. Pressures to reduce first cost are extreme and, since margins increase the size of the ship, they are a frequent area to be attacked.

Growth

After completion a ship will grow in weight for many reasons including the following:

(*a*) Layers of paint, particularly in weatherwork areas. During the LEANDER modernizations up to 80 coats of paint were found in some places, with a total weight of about 40 tons.

(*b*) The hoarding of extra stores, tools, etc., which may be needed one day. This item too was believed to be about 40 tons in the LEANDERS.

(*c*) Authorized As & As and repairs.

(*d*) DIY improvements to living spaces and additional personal effects.

On average, frigates grow in weight at about 0·5% per annum and the centre of gravity will rise by 0·3% per annum. As a direct result, liquid loading restrictions become more severe as the ship gets older and heavier.

Much of the extra weight is unavoidable but every effort should be made to restrict growth to as low a figure as possible. In particular, equipments, stores, etc. which are never used should be disposed of. The stability, as measured by the metacentric height, must not be too great. It has long been realized that ships which are too stiff have unpleasant rolling characteristics. Ships with a high value of GM will roll worst with seas forward of the beam while low GM ships will find seas abaft the beam the worst condition. Roll amplitude is not affected very greatly by changes in GM but the stiff ship will suffer much greater acceleration. (FIG. 8) Since the human brain will measure angles from the *apparent* vertical, the perceived roll will be much greater in the stiff ship. Handling of heavy equipment (e.g. helicopter re-arming) will be very difficult if GM is excessively large.

Inclining Experiments

The first of each new class of ship and at least one other ship will be inclined on completion. The experiment consists of moving weights across the deck, applying a known heeling moment, and measuring the resulting angle of heel. Since the position of the metacentre is known from the hydrostatic curves for the draughts at which the ship is floating, it is then possible to determine the position of the centre of gravity of the ship as inclined.

Simple but extensive calculations of the weights to go on or off, at various positions, to reach the deep or light condition can then be made to determine the stability in all seagoing conditions. A special harbour or docking condition may also be worked out since the stability of a ship as it touches down on the blocks can be critical.

Certification

When the ship design project has completed and checked the calculations, the results are inspected by the Chief Naval Architect's staff to ensure that all appropriate criteria are met. A marginal fail in one criterion is sometimes accepted if if is clear that, overall, the margin of safety is adequate. Since the full calculations take a considerable time to complete a signal will usually be sent when the preliminary results of the inclining are available to say that stability appears satisfactory pending the full results.

It is sometimes necessary to recommend restrictions in the stowage of liquids or in the operation of the ship. Such restrictions are discussed with CSO(E)'s staff and are imposed only when seen as essential to give normal safety standards.

When the Chief Naval Architect, personally, is satisfied with the stability of the ship he will sign and issue the Stability Statement which sets out the metacentric height in different loading conditions and lists any operating restrictions. Curves of stability (GZ) accompany the statement. Normally the statement is valid for ten years at the end of which period the ship is re-inclined. Ships are often inclined before a refit involving additional equipment fit, to ensure that unplanned weight growth is not excessive. A further inclining will take place after the update.

The preservation of adequate stability needs unremitting care from both designer and operator.

My thanks are due to my colleague, Mr Martin Cawte, for his help.

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