# WEATHER AND WARSHIPS

## PAST, PRESENT AND FUTURE

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*This article is based on a presentation given by the author to the Royal Institution of Naval Architects (RINA) in February 1995.*

ABSTRACT

During the nineteenth century the design of warships for seakeeping developed in the form of a series of guidelines, based on experience but guided by FROUDE's theory of the behaviour of ships in waves. The principal requirement was firstly to prevent capsize and secondarily accurate gunnery which directed attention to rolling. Later freeboard became important. During World War II attention shifted to anti-submarine warfare, firstly in maintaining speed in a seaway and later in operating helicopters in bad weather. Limitations on human performance were perceived as important. The development of the strip theory together with that of powerful computers made it possible to quantify many more aspects and also to consider the variation of multiple parameters in the design stage.

### Introduction

From about 1860 it was slowly recognized that the behaviour of a warship in waves affected its ability to fight and even to survive. Experience, sometimes tragic, led to the development of empirical guidelines which were generally sound. Though the basic theory of motion in waves was established by William FROUDE in 1860 and developed in his later papers, the equations could not be solved in real cases and some simplifications proved misleading.

Since World War II, the requirement for surface ships to hunt fast submarines has led to greater emphasis on the need to maintain speed and operational capability in a seaway. Following initial success using highly tuned empiricism, the development of the strip theory, probability theory and of powerful computers has enabled the designer to meet specified criteria. Suitable criteria for performance of people and weapons have also been established but it remains difficult to quantify the operational importance of improved seakeeping (FIG. 1).

## THE PAST

### The nineteenth century

Motions were not seen as of great importance in fighting between wooden sailing ships since their design was so heavily constrained. There was little chance of a superior design[1,2] whilst the principal motion, rolling, was well damped by their sails.[3] The introduction of large iron ships with a very different distribution of weights, particularly with armour and gun turrets, and less damping led to problems. In particular, there was a fear that heavy weights near the ends would lead to heavy pitching and, in consequence, the bow and stern of H.M.S. *Warrior* were unarmoured.[4] The belief that a low moment of inertia was needed to reduce motions was to persist until well after World War II. Though apparently soundly based, it will be shown later that, when quantified, the effect is insignificant. (See the note on the wetness of *Narvik).*

FROUDE's theory of rolling,[5] presented to the RINA in 1861, established most of the principles affecting the behaviour of ships in waves, but it was not usually possible to obtain numerical solutions in real cases. In consequence, two of his main conclusions, though correct, were misinterpreted. Low moment of inertia

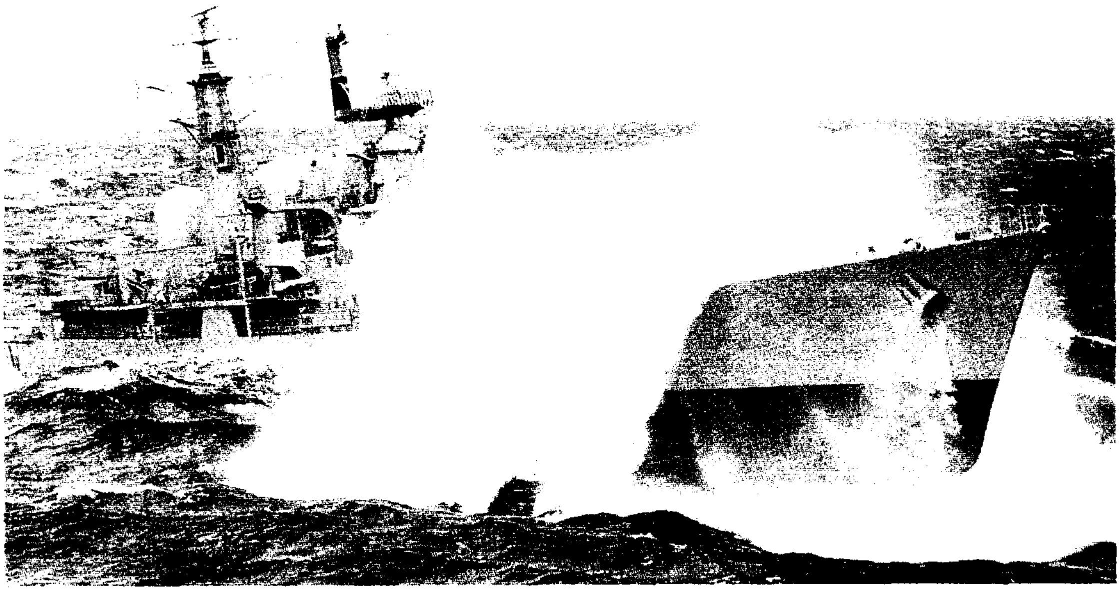

FIG. 1—H.M.S. 'MANCHESTER' PITCHING HEAVILY OFF AUSTRALIA
AS WELL AS BEING WET, SHE WOULD HAVE BEEN USING UP HER FATIGUE LIFE

has already been mentioned but, more important, he showed that a small metacentric height (GM) led to a long roll period which tended to reduce rolling. Though he made it clear that GM needed to be sufficient for stability, misunderstanding of his work led to some battleships and many passenger liners being designed with inadequate GM.

## Rolling and capsize

For a decade or more, the link between stability and rolling was debated with the fervour of a religious war. The need for ever thicker armour led to pressure to reduce the freeboard and hence the extent of armour, whilst the need to site heavy gun turrets on the upper deck also favoured low freeboard ships. In the 1860s the metacentric theory of stability was well understood but no practical method of solving ATTWOOD's equations for large angle stability (GZ) was available until the end of the decade and hence the importance of freeboard at large angles was not recognized. In 1870 the battleship *Captain* capsized in a moderate gale on her third voyage with the loss of about 500 men. The direct cause was the combination of low freeboard with the overturning moment of a full sailing rig. This was exacerbated by inadequate estimating, by the builder, of weight and of the height of the centre of gravity above the keel. But, more important, was the way in which politicians and press bowed to unqualified views rather than those of their own seamen and naval architects.[6]

The inquiry into the loss of the *Captain* was extended by a second, more comprehensive inquiry into the safety of other existing and planned battleships.[7] The case of the GZ curve was argued and generally accepted though it was also realised that acceptable and safe criteria for large GZ could only be established from experience. The committee was a mixture of seamen, scientists and engineers including RANKINE and FROUDE. The press and politicians had misread the lessons of *Captain* and believed that low freeboard was always dangerous, but naval architects maintained that, without the heeling moment of sails, such ships could be safe. There was also pressure for very low freeboard, as water washing over the deck was seen as providing effective roll damping. Some seamen and some naval architects also claimed that speed in head seas could be better achieved with a low freeboard ship piercing the waves rather than rising to them. The fallacy of this argument only slowly became apparent.

The emphasis was on the accuracy of gunfire, particularly on the beam so that rolling was still seen as the most important motion. FROUDE in a series of model tests and full scale trials had shown the value of large bilge keels but, as he pointed out in 1872[8], this work was not properly applied and for at least a century bilge keels tended to be too small.

## Freeboard and wetness

Towards the end of the nineteenth century, a number of factors directed attention to freeboard and wetness. The introduction of the quick firing gun led to a numerous secondary battery. As a measure of protection, these guns were mounted in casemates, widely dispersed, both horizontally and vertically. It was found that the main deck guns, sometimes as little as 10 feet about the design waterline[9], were unusable in a seaway and in the battle of Coronel (1914), nearly half the guns of the older British ships could not be used. These low gunports could not be made watertight and contributed to the loss of several ships following underwater damage. Experience with destroyers, after 1892, showed freeboard as even more important. It was seen as desirable to keep them low to make them less visible in night torpedo attacks, whilst weight saving was essential. The 115 ships of the early classes were designed by their builders to a loose specification, which included heavy penalties for failure to achieve their trial speed–sometimes a bonus for exceeding the speed. The French designer, NORMAND, referred to such ships as:

'Machines designed to run a trial trip'.

Rather slowly, it was recognised that these high trial speeds in calm water meant little. In order to achieve them the builders:

- Picked teams of skilled stokers, often far more numerous than carried in service.
- Sieved the coal to ensure optimum combustion.
- Undertook the trials when the sea was calm.

The best speed in service was some 3-4 knots less and wear on over stressed machinery soon reduced this even further.

These lightly built ships frequently suffered damage in rough weather[10] and in 1901 the *Cobra* broke in half. The exact cause of this disaster was, and remains, a matter of debate.[11] But, there is no dispute that she was weak and that she was only slightly weaker than many other destroyers in service. The next class, the RIVERS were designed for 25 knots instead of 30, were stronger and had a freeboard forward of 16 feet (much in line with World War II guidelines) instead of 8½ to 10 feet in earlier classes. It was soon found that the RIVERS were actually faster in most sea conditions than the earlier boats.

Destroyer design advanced with bigger ships until during World War I a major advance was made in the V&W class. They were bigger—which always helps seakeeping—and, based on experience at sea, their designer, HANNAFORD, moved the bridge further aft to reduce the amount of spray hitting it. By moving it aft (29%L, instead of about 23%L, in earlier ships) the vertical accelerations at the bridge were lessened by about 26% giving them a slightly undeserved reputation as seaboats. A more debatable lesson of that war came from the light cruisers. The early war built ships were found to be very wet and it was decided to give later ships more sheer to increase freeboard forward. In ships under construction the sides were carried vertically up from the original forecastle deck to the new sheerline, forming a knuckle. These ships were certainly less wet but whether the improvement was due solely to increased freeboard or to the form of the knuckle remains hotly debated.[12]

## World War II

The Battle of the Atlantic involved action between very dissimilar marine vehicles, surface ships and submarines, affected very differently by weather. There are many excellent accounts of life at sea in various classes of escort vessel from which it is easy to establish an order of merit for sea keeping. Not surprisingly, size, primarily length, appears as the dominant factor. The performance of these wartime ships has recently been examined by LLOYD[13] using a much simplified version of current theory[14] and the estimates of the percentage of time in which their performance was degraded by motions (Table 1), seems to match well with subjective accounts.

TABLE 1—*Operational capability of World War II destroyers*

| **Class** | **Length** (m) | **Days lost due to motion** (%) |
|---|---|---|
| FLOWER | 60 | 28 |
| CASTLE | 72 | 21 |
| RIVERS (Old destroyers) | 90 | 15 |
| LEANDER (Today) | 108 | 9 |

Subjective accounts of motions and their effects can be of great value but require careful interpretation. It is of little value to comment that:

"XXXX is a good seaboat"

It is surprising how often this bland comment is used today in sales literature. The seaman will usually concentrate on one aspect which may be:

- The perceived motions at the bridge.
- Wetness.
- Perhaps most often, slamming. (Slamming—severe impact loading associated with pitching).

The study of photographs of ships in heavy seas is also of value, particularly in the topic of wetness. It will often be useful to compare a photograph with a computer simulation of the same event.

The behaviour of the German *Narvik* class of World War II forms a good example of the interpretation of reports from sea. The later ships had a twin 5.9 inch turret on the forecastle adding 50 tons well forward to a displacement of 3000 tons. Reports from sea stated that they pitched much more heavily and were now very wet. This seemed improbable and LLOYD studied their behaviour using a well proven program.[15] At 20 knots into Sea State (SS) 5 (wave height 3.25m), it was estimated that significant pitch would increase from 2.60 to 2.62 degrees. On the other hand, freeboard forward would reduce from 6m to 5.78m and this would be sufficient to increase the probability of a wave causing water to come inboard from 0.76% to 1.2%—nearly double. Thus the reports that the increased weight had made the ships wet appears fully justified, but the seaman's explanation that this wetness was caused by increased pitching was wrong.

It is surprising that there are no records of warship losses from broaching in which the stern is lifted on a following wave of about the speed of the ship whilst the stem digs into the trough. In this condition the orbital velocities much reduce the effectiveness of the rudder and the ship will fall rapidly into the trough, broadside on to the waves. Such incidents are not uncommon, even in modern warships. Broaching is not fully understood and is difficult to represent in model tests. A deep rudder is helpful whilst there is some evidence that transom sterns made a broach more likely. In following seas, ship speed should be much less or more than wave speed.

### Losses in bad weather

Loss and damage even to big and modern, undamaged ships in severe weather was not uncommon in World War II. Of destroyers, the USN lost 4[16], the Italians 2 and the Russians 1 due to flooding and capsize. The Japanese lost a destroyer from capsize in a storm, just before the war, which also caused serious structural damage to larger ships. In addition, the French navy lost a small destroyer which broke in half. There were no such losses in the RN. A typical scenario was slow flooding as a result of severe motions through openings and damaged hatches.[17] This led to loss of auxiliary power and hence steering and progressive loss of stability until the ship was finally swamped. Severe damage to battleships and aircraft carriers occurred from time to time. Destroyers were long, shallow and fast and, as a result were prone to slam. Other classes of escorts were generally too slow to slam. It is interesting that seamen will very often equate absence of slamming with good seakeeping.

### Glimmers of humanity

Little consideration was given to what is now called human factors. Accommodation for ratings was right forward where motions were most severe and access to duty stations—and even the galley—was often over an open and wave swept deck. Leaking rivetted seams made the mess decks wet as well as contaminating feed water. Heavy rolling was a particular—and generally unnecessary—problem in several classes due to inadequate bilge keels. This first became obvious in the FLOWER class but was much more severe in the CAPTAINS![18] These ships were withdrawn from service for bilge keels to be increased in depth from 18 to 24 inches (and also lengthened) while weights were added to reduce GM and give a greater roll inertia, increasing the period from 8 to 8½ seconds. Two pairs of ships were tried in company and the maximum roll angle was almost halved whilst subjective reports from sea were enthusiastic. There is no simple rule of thumb for sizing bilge keels but had the empirical procedure demonstrated by FROUDE been followed, these ships would have been operationally effective much sooner.

## THE PRESENT

### Anti-submarine warfare and seakeeping

It may seem strange to refer to the whole half century since the war as 'present' but the requirements for seakeeping have changed only slightly though the tools available have improved out of all recognition. The objective has been protection of shipping which, initially meant keeping up with fast submarines with the speed of the frigate in head seas as the design parameter. Gradually this changed as nuclear submarine speeds increased and the requirement to operate helicopters in very severe sea states, leading to the vertical velocity at the landing spot being the critical parameter affecting the aircraft. Whilst accelerations, both vertical and lateral, may limit the performance of the deck crew. The complete picture, summarized in (FIG. 2), involves motions with six degrees of freedom, each with amplitude, velocity and acceleration, of which any or all may be important, together with other factors such as sea state and course.

Helicopter pilots will usually claim that they can take off and land in almost any sea state provided that the ship can adopt a favourable speed and heading to take advantage of the occasional quiescent period. The limiting factors for long term

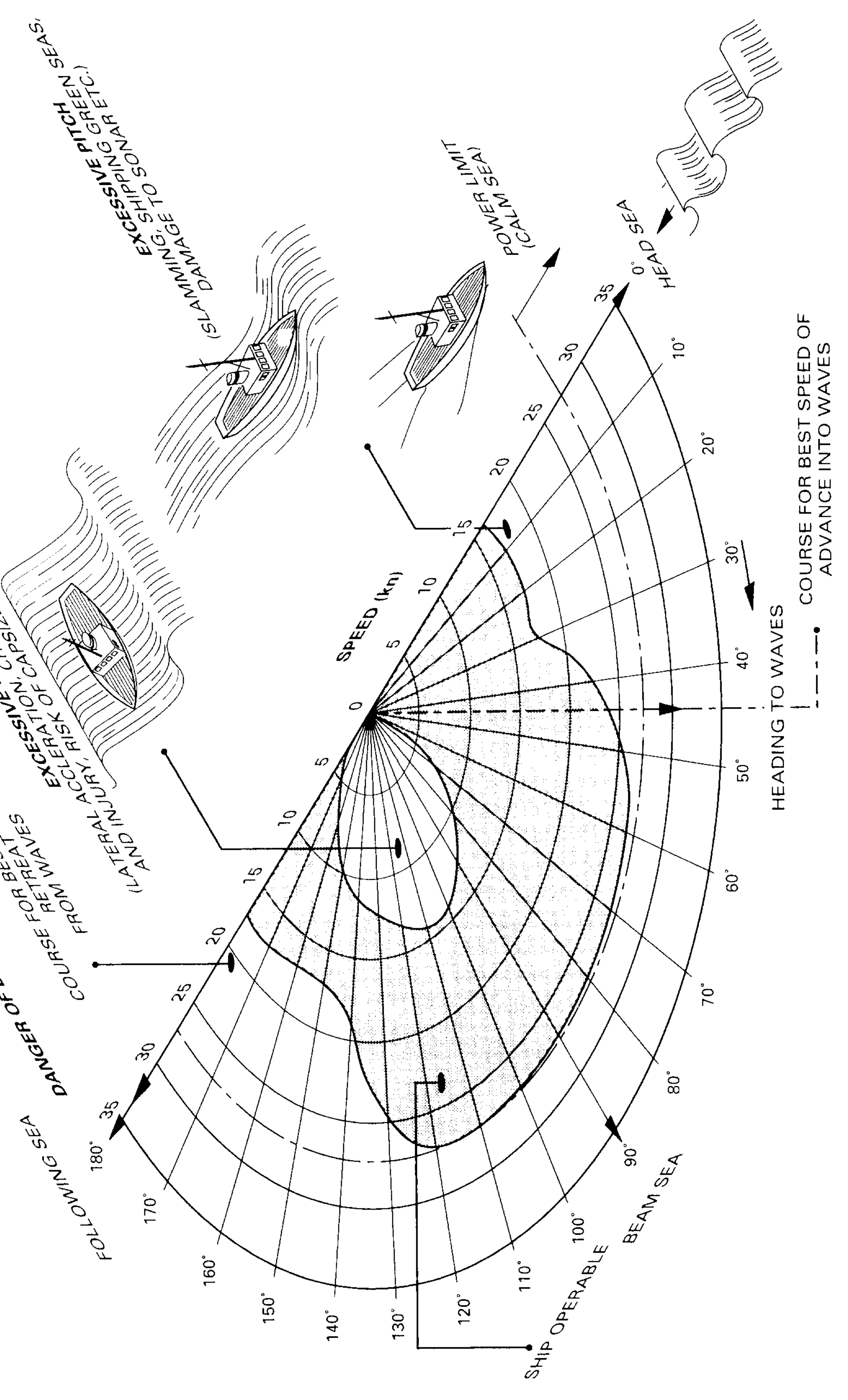


FIG. 2—TYPICAL OPERATING REGIME FOR A FRIGATE IN THE NORTH ATLANTIC

operation are likely to depend on flight deck activities, particularly re-arming, dominated by lateral and vertical accelerations. Wind speed over the deck, independent of motion, may limit such actions as rotor blade folding.

## Post War frigates

The post war frigates of the WHITBY class were the apotheosis of empiricism and set a standard of sea keeping which remains hard to beat. The form was derived by N.G. HOLT, a keen yachtsman and refined by GAWN with model tests at Haslar. They were given a high freeboard forward and a high rise of floor, combined with very fine waterlines forward. They were fairly deep draught to obtain good sonar immersion and permit large propellers which also pushed the onset of slamming to higher speed. Their heavy weights were concentrated amidships to reduce moment of inertia which also brought the bridge close to amidships, reducing vertical acceleration on the bridge. Today, one would disagree with the fine waterlines and regard moment of inertia as unimportant but agree with the other features. At the time, fine waterlines were seen as most important and the following class, the TRIBALS were given a low prismatic form both to improve endurance at a high cruising speed and to give even finer waterlines forward. This proved unsuccessful, showing the limitations of subjective design, and, in particular, it was found that their form experienced peak slamming pressures much further aft that in earlier ships, leading to structural problems.

In October 1977 a comparative seakeeping trial was held in which *Hermione* (LEANDER class) and *Gurkha* (TRIBAL class) steamed in close company, at high speed, up to 20 knots, in severe weather; waves up to 7.8m significant height.[19] Pitch angles were almost indistinguishable and there was little different in heave though the *Gurkha* was consistently but slightly worse (FIG. 3). Vertical acceleration at the bridge was about 20% greater for the *Gurkha* since her bridge was appreciable further forward (*Gurkha* 26%L, *Hermione* 36%L) and it seems likely that this aspect accounts for the TRIBAL's poor reputation as a seaboat. The slamming results were inconsistent; at 12, 14 and 18 knots the frequency of slamming was appreciably less in the *Gurkha* but at 16 knots slamming was so severe in the *Gurkha* that the trial was almost abandoned. The trial was finally abandoned when three very violent slams at 20 knots in the *Gurkha* caused whipping damage. It was also noted that slamming was much more irregular than in the *Hermione*. Wetness was only recorded on the LEANDER but was not seen as a limiting factor. Sickness was much more common in the crew of the

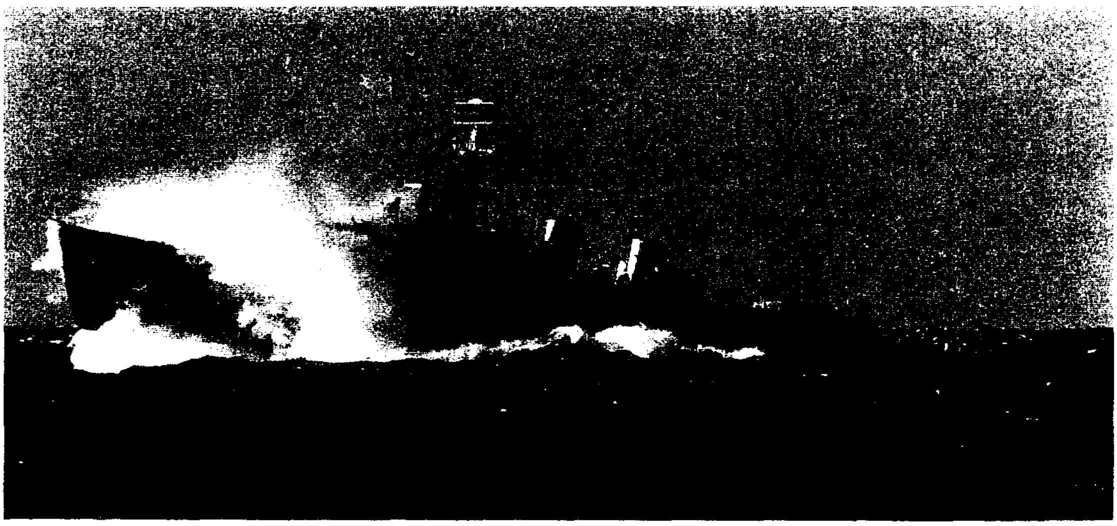

FIG. 3—H.M.S. 'GURKHA' DURING COMPARATIVE TRIAL WITH 'HERMIONE'.
SOME 20% OF HER LENGTH IS OUT OF THE WATER

*Hermione*, but this was explained in part by the greater acclimatization of the *Gurkha's* crew.

This trial was also intended to evaluate the accuracy of contemporary programs, discussed later, and as part of a programme to estimate long term structural loading. It was noted that whipping added considerably to the maximum static stress due to wave loading and also brought further forward the point at which the combined maximum occurred.[20] In more recent years long term strain measurements have been carried out on a number of British warships to determine lifetime loadings, both extreme and mean.[21]

## Strip theory

A classic paper by St DENIS and PIERSON[22] in 1953, together with the growing power of the computer led to the strip theory of ship motions which has been developed into a powerful tool. In this theory the hydrodynamic forces are estimated for a number of transverse strips and these are then summarized over the length of the ship. The theory itself will not be discussed in this article (see LLOYD[23]) but only its accuracy and application. The 1977 trial, discussed above, was a test of the accuracy of strip theory in its early form. Estimates of pitch and heave were already sufficiently accurate to be used by designers, but those of deck wetness were far out as the theory did not allow for the distortion of the incoming wave by the ship itself or for the effects of the above water form in projecting water away from the hull. This has proved difficult to solve but recent work shows some promise.

## Roll damping

Between the wars there were many problems in anti-aircraft (AA) fire and a solution to one of these, rolling, was sought in the use of active systems. The sloop *Bittern* was fitted with fin stabilisers of Denny-Brown type in 1936 and sufficient success was achieved to justify fitting to a number of AA escort vessels in the war. However, control engineering was in its infancy and the fins were not entirely successful. Since they were heavy and bulky, they were removed from some ships to increase fuel stowage. Of the first generation of frigates, only the AA LEOPARD class were fitted. Fins were proposed for the TRIBAL class and fitted without much debate as their unusual machinery layout made installation relatively easy. Non retractable, multiple pairs of fins were fitted in the COUNTY class which overcame the problem of space at some loss of hydrodynamic efficiency.[24] Since then most RN ships, as well as those of most other navies, have been fitted with fins but, while most naval architects and officers are convinced of their value, no evaluation of their value in terms of operational effectiveness has been published.

Many model tests and some ship trials have shown that rudders may be used to reduce rolling.[25] Trials with the USCGC *Jarvis* in 1979, using the rudder as a stabilizer, showed:

- A maximum roll reduction in beam seas of 31—49%.
- 22% in bow seas.
- 28% in quartering seas.

These results compared well with earlier simulations. The effect of sea state was only measured for quartering seas in which reduction was 28% in SS 4 and 8% in SS 6. These are thought to be typical results using existing steering gear but much greater roll reduction should be possible using systems designed both to steer the ship and reduce roll. In frigates it is undesirable to fit bilge keels abaft the fins because of the noise and vibration caused so the use of rudders will have the incidental, but very important, result of permitting bigger bilge keels. More recently, it has been suggested that big, inclined rudders may also be used for pitch stabilization.[26]

Attention has been drawn to the inadequate size of bilge keels in many ships in the century following FROUDE's work and in 1987 MONK published a criterion for sizing bilge keels.[27] He took the lateral acceleration on the bilge in SS 5 due to rolling as the parameter and suggested that it should not exceed 1.5m/sec$^2$. This approach has been applied to a number of classes of ship in which the original bilge keels were so inadequate that larger keels were fitted and 'before and after' studies support MONK's criterion. However, its use in design depends on estimated roll accelerations using computer programs. BROOK[28] showed in 1989 that available programs gave very different results and none of them forecast roll behaviour very accurately. This does not invalidate MONK's criterion but it does mean that it can only be used with one specific program and numerical values matched to that program and to ships at sea.

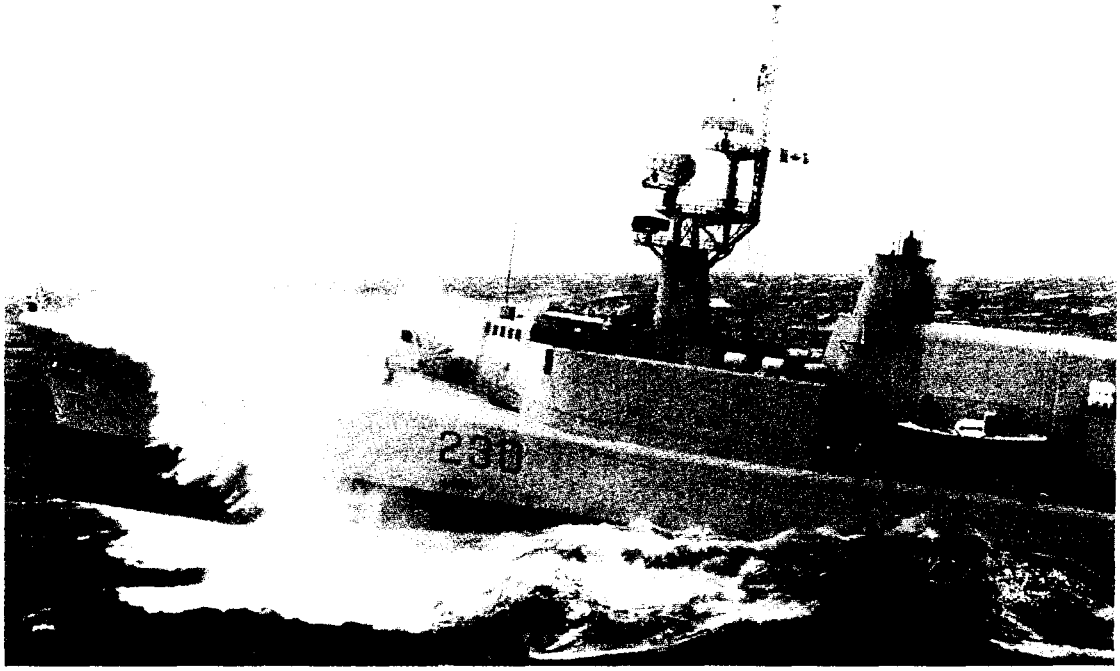

FIG. 4—H.M.C.S. 'MARGAREE' IN ROUGH SEAS
A TURTLE DECK FORECASTLE WAS INTENDED TO TURN SEAS AWAY QUICKLY

## Wetness (FIG. 4)

Mention has already been made of the problems in estimating the occurrence of green seas on the deck using the strip theory. Spray presents greater difficulties as its trajectory depends on the above water hull form—flare—which is assumed vertical in strip theory. Droplet size depends on surface tension and cannot be examined in conventional model tests. Model tests do indicate areas of the side at which spray is generated and it is sometimes possible to examine the trajectory using smoke in a wind tunnel. A great deal can be done by common sense design; much spray is generated by projections such as anchors, external plate laps and gun platforms, all best avoided near the bow. Flare does help to throw spray clear of the deck (as do knuckles) but, if overdone, it can also generate spray and even lead to slamming.[29]

## Criteria

Despite its faults, strip theory can give the designer invaluable assistance in estimating the behaviour of his form in waves. This is only useful if it is known what motions etc are acceptable and, as with many design problems, deciding what you want to achieve is often the hardest part. Acceptable limits on motions and other aspects of behaviour in rough seas are set by their effect on people, weapon systems (including aircraft) and on the ship itself. In many cases there are multiple limits and a great improvement in one aspect may merely expose a different limit, close behind. An important example of this is in helicopter operation, generally limited by the vertical velocity of the landing spot and accelerations on the flight deck. If these motions are greatly reduced, as in a SWATH, helicopter operation will still be limited by wind speed over the deck and the overall benefit in days of operation may not be large.

People liability to sickness is governed by vertical acceleration and is very largely confined to the frequency band 0.15—0.30 Hz. Typically, a vertical acceleration of about 0.08g is seen as the limiting value for naval crews over a period of time. KARPPINEN[30] recommends alternative criteria for different tasks and for passengers. However, susceptibility to sickness is also dependent on other factors of which the most important is acclimatization followed by the time and nature of the last meal, fresh air/smells and view of the horizon. Amplitude and frequency are usually combined in an empirical factor, the Subjective Motion Magnitude (SMM)[31]. In peace time operations it is found that captains alter course or speed to reduce motions if the SMM exceeds 12 but since motivation is important, it is likely that a higher value would be accepted in war. Decision making is thought to be degraded by motions but no numerical link has been reported. It may well be the case that accepting a higher SMM further degrades the ability to make a correct decision. BROWN and MARSHALL have suggested[32] that the long term average SMM should not exceed 4 which was used as a design criterion for the CASTLE class. It has long been known that motion is least near amidships but the magnitude of this effect was not recognized until computer based estimates became available.

The ability to carry out manual tasks is largely governed by lateral acceleration. BAITIS et al[33] have defined a parameter Motion Induced Interruptions (MII) which represents the frequency with which a task is interrupted by the need to hang on or by a stumble. The relationship between MII to lateral acceleration is shown in Table II:

TABLE II - *Relationship between MII and lateral acceleration*

| RMS Lateral accn-g | MII per minute | Risk |
|---|---|---|
| 0.08 | 06 | |
| 0.10 | .5 | |
| 0.12 | .7 | Serious |
| 0.14 | 1.3 | Severe |
| 0.16 | 2.0 | Extremely hazardous |

Roll forces are also most important in ships carrying aircraft (helicopters) as they may slide overboard into the sea. The coefficient of friction between a deformable surface (tyre) and a rough deck is variable depending on loading and relative speed. It is not easy to develop a flight deck paint which will last, provide corrosion protection, withstand landings and the dragging of packing cases and be suitable for deck hockey, all while dry, wet or soaked in oil.

The numerical values of many criteria are a matter for debate though there is more general agreement on the form they take. Some illustrative values of acceptable criteria are:

Slams 20—90 per hour (The lower value should be used for hull mounted sonar).

| | |
|---|---|
| Deck wetting | 30—90 per hour (Note *Hermione* reached 120/hr) |
| Propeller emergence | 40—120 per hour |
| Sonar emergence | 80 per hour |

Helicopter operation has many limits. Each stage of the operation from maintenance, refuelling, rearming, take off and landing is affected differently by the weather.[34] The key attributes, with some RMS limiting values, for a typical helicopter are:

| | |
|---|---|
| Vertical velocity | 2m/s |
| Pitch | 2° |
| Roll angle | 2½° |
| Vertical and Lateral acceleration | 0.15g & 0.25g |

There are also limits on wind speed and direction which vary with different aircraft type. In addition, advantage may be taken of the occasional 'quiescent period' which occurs even in severe storms. The most effective way of reducing motions is to move the landing spot close to amidships.

Other weapon systems are affected by motions. For example, the probability of a hit from a modern stabilized gun mounting at 7,000 metres was reduced from about 37% in calm water to 10% when the vertical velocity at the mount was 3 m/sec.

## Cost and value

The cost of improving seakeeping should not be large, a small increase in length, accompanied by an increase in freeboard, costs very little if the additional structure is recognized as a 'hydrodynamic appendage' and not as space to be filled with further expensive equipment. Bigger bilge keels are even cheaper. The value of seakeeping is harder to establish as weather is ignored in most operational research studies.

BROWN has suggested[35] that the value of an operational day must exceed the cost of providing it. From the cost of the frigate force given in the Defence Estimates, together with the number of ships and days at sea, it was estimated that it costs about £100,000 to provide a frigate at sea for a day. Discussion with the naval staff produced the figures in Table III which are for the loss of operational capability in various sea states for a typical frigate. It should be noted that most of this loss of capability is associated with degradation of crew performance and hence cannot be reduced by weapon system stabilization.

TABLE III—*Loss of operational capability*

| Sea State | Probability of Occurrence % Days (4) | % loss of Capability | Note |
|---|---|---|---|
| 0–4 | 39 | 0 | |
| 5 | 31 | 10 | 1 |
| 6 | 21 | 30 | 2 |
| 7 & over | 6 | 95 | 3 |

Notes: (1) Inconvenience, work takes longer, some effect on sonar.
(2) Up to one third crew sick, sleep difficult, all exhausted, helicopter operation difficult, many weapons degraded.
(3) Ship is ineffective as a fighting unit.
(4) Probability before recent increase in average wave heights. (See ref 36)

This approach is crude but must underestimate the true loss of value in peacetime, whilst in war the small advantage over the enemy is of incalculable value. A comparison between a frigate of 108m length and one of 125m shows a net present value gain of £3 million to the larger ship over its life. (Discontinued at 10%). Since these figures were derived, the cost per day has probably changed little in real terms but HOGBEN has shown[36] that over 30 years, the average wave height in the North Atlantic has increased by 1-2% per annum, greatly increasing the benefits from improved seakeeping.

## THE FUTURE

### Value

This final section is, inevitably, a more personal view of the way ahead. The first step must be to establish more soundly based figures for the loss of capability due to motions etc. ('etc.' is short hand for wetness, slamming and other indirect consequences) and from these to establish a cash value which can be used in trade off studies between the cost of seakeeping measures and other military aspects. Such value analysis can also be used to support research work on seakeeping. It should be unthinkable for operational analysis of naval tasks to neglect the effect of rough weather.

### The monohull

Once the need to improve seakeeping is established, the designer can begin a series of trade off studies which will go into increasing detail at each stage. In the first stage it will be assumed that the form is 'good' and only dimensions will be varied. Increase of length will reduce the amplitude of pitch angle and heave but the lever effect at the ends will increase relative motion there. In consequence, the longer ship will require more freeboard to maintain the same frequency of deck wetting. It should be remembered that the effect of length on motions is non-linear; a small increase in length will make a great difference to a short ship whilst a proportionate change to a longer ship may have little effect.

Increase of length has another benefit which may well prove more important than mere reduction of motions. The designer has greater freedom to arrange key spaces such as the helicopter deck, operations room and accommodation in the minimum motion zone. This was a principal feature of the CASTLE class design and the high praise which it has won for seakeeping[37] is probably because the crew are less exposed to motions. There is evidence[38] that ships whose bridge is far aft will be driven harder in head seas and hence may be more likely to suffer damage.

The draught of the ship and its deadrise forward must be sufficient to reduce slamming to acceptable levels. Subjective reports from sea are very sensitive to slamming; a ship which does not slam, perhaps because it is slow, may be described as a good sea boat for no other reason. For similar section shapes, the main parameter is draught—not, as is the case for freeboard, its ratio to length. The effect of beam on rolling is complicated but excess beam and hence metacentric height will lead to a small increase in roll amplitude and a considerable increase in roll acceleration. The margin between sufficient beam for stability and that which causes rapid roll is small in modern warships.

The paragraphs above indicate that, for a ship with given displacement, length, draught, freeboard and, to a limited extent, beam, should all be increased. This will lead to a low block coefficient which is not particularly desirable from the seakeeping point of view, will lead to poor large angle stability and certainly lead to problems in layout. The search for the best compromise between even this number of variables is not easy and becomes even more difficult in the next stage when the shape as well as the proportions of the ship must be considered.

## The Seakeeping Package

Many seakeeping programs based on strip theory are available which may be used to estimate the motions and other rough weather phenomena such as slamming and deck wetness for any specified design. If these responses are considered unacceptable the design may be changed and the program run again to see the effect of the changes. Some guidance on desirable changes may be obtained from the literature though such advice is often difficult to apply since it may depend on different assumptions, not always clearly set out, and because most such advice implies changing one form parameter at a time.[39]

In 1991, LLOYD introduced the 'Seakeeping Design Package' which went far to overcome these difficulties.[40,41] In its present form the Package seeks to design a hull to achieve four target responses set by the designer. These are the RMS vertical accelerations at two positions together with the probabilities of wetness and slamming. The designer also chooses the maximum and minimum values of 12 hull dimensions and form parameters (length, beam, draught, midships area coefficient etc). The Package then finds the form which comes closest to achieving the four targets.

One or more targets may be omitted, for example:

(*a*) A low probability of wetness may be chosen allowing motions and slamming to take their own values. In this case the Package would select the shortest permitted length which would tend to contour the waves, remaining dry at the expense of high accelerations.

(*b*) Low accelerations can be selected with wetness and slamming responses free. Then the Package would select the longest ship which would be comfortable at the expense of frequent wetness and slamming.

These two simple examples illustrate the conflicting demands imposed on a real design required to have generally 'Good' seakeeping in which accelerations, wetness and slamming would all be important. In a practical design, the Package will make the necessary compromises between these conflicting requirements and offer a balanced design matching the requirements as far as is possible. This approach has enormous potential and should be developed by comparing its predicted behaviour with the results of past and future seakeeping trials.

There remain areas in which further research is needed. Roll prediction is still unsatisfactory though estimates of roll damping are quite good. Developments in roll prediction will enable the value of active devices such as fins, the use of rudders and tank stabilisation to be properly assessed. The effect of above water shape on wetness–flare and knuckles–remains very uncertain.

## Novel forms

For most naval tasks the monohull is an effective and economic compromise. However, if seakeeping is seen to dominate the requirements either as minimum motions or as maximum speed in severe seas, there are a number of specialised craft which merit consideration. These can only be listed here, together with the briefest of notes on their advantages and disadvantages.

### *SWATH*

The SWATH can offer the lowest motions of any surface vessel. It will be slightly more expensive that a monohull for the same payload but far cheaper that a monohull with the same motions. Care is needed in identifying other limits which will come into play when motions are reduced—helicopter operation will be limited by wind speed. In northern latitudes the SWATH has a great deal to commend it but if operations will only take place in sheltered waters, the cost may not be worthwhile.

*Trimaran*

The trimaran as described by PATTISON[42] is also called the ILAN (Incredibly Long And Narrow) and indeed it is just that. A very long and narrow ship, held upright by outriggers with the advantages and disadvantages outlined above.

*Catamaran*

The conventional catamaran has such high roll accelerations that it is rarely appropriate for work in the open sea. Its large deck area and high stability do make it valuable for some tasks and the severity of roll can be reduced to some extent by waisting the hulls. The surface piercing catamaran has similar advantages and disadvantages and is said to have problems in quartering seas.

*Hydrofoils*

The submerged foil hydrofoil is likely to prove the best for high speed in seas up to its limits. The surface piercing hydrofoil has a lower performance at much lower cost.

*Hovercraft*

The fully skirted hovercraft has, for a given payload, a seakeeping performance which is inferior to hydrofoils but superior to most surface riding craft.

It is very difficult to evaluate such vessels in comparison with monohulls as not only is their performance different but it is unusually highly tuned whilst the distribution of costs through life may differ considerably. Some comparative values for the vertical acceleration at the bridge of existing small craft (ca. 200 tonnes) in 1.5m (significant) waves are shown in Table IV.

TABLE IV—*Vertical acceleration comparative values*

| Type of Craft | Acceleration, g |
|---|---|
| Fast Patrol Boat | 0.16–0.18 |
| SWATH | 0.03 |
| Hydrofoil—submberged foil<br>—piercing | 0.02<br>0.04 |
| Hovercraft | 0.05 |
| SES | 0.20 |

## Closing thoughts

It is most important that the designer and the research worker go to sea, frequently, in bad weather. The horror of sea state 7 is not fully represented by differential equations. The naval staff and the designer must work together to ensure that the essential criteria are set out clearly and understood in the same way by everybody. The designer must use every tool available; theory, experiment, trials and historical evidence as well as listening carefully to the views of sailors.

## Acknowledgement

My thanks are due to Dr Adrian LLOYD who has been my tutor in this subject for some 20 years and who has also made valuable direct contributions to this article. The views expressed are the author's and not necessarily those of any other individual or organization.

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