SEAWORTHY BY DESIGN

BY

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(*Sea Systems Controllerate*)

ABSTRACT

The paper reviews the present state of seakeeping knowledge as it is applied to the design of surface warships. Modern theory gives fully adequate estimates of most ship motions but evidence is still scarce on acceptable criteria for the operation of weapons, sensors and their crews in bad weather. It is suggested that improved seakeeping is a cost-effective way of increasing the fighting effectiveness of the fleet.

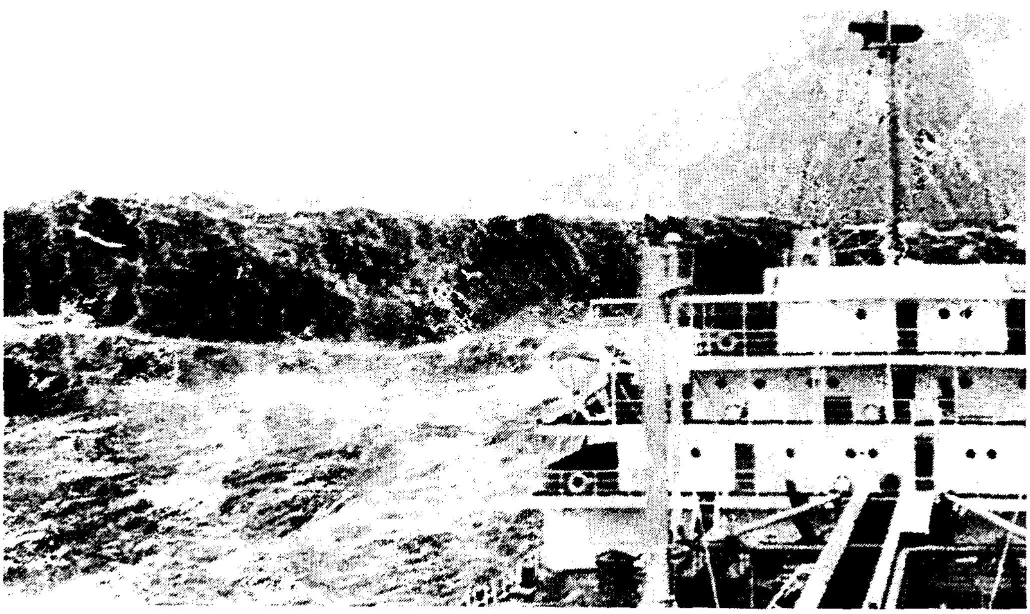


FIG. 1—SAID TO BE THE LARGEST WAVE EVER PHOTOGRAPHED. SOURCE UNKNOWN; PROBABLY A TANKER OF ABOUT 12 000 TONNES

There be three things which are too wonderful for me, yea, four which I know not,
The way of an eagle in the air;
The way of a serpent upon a rock;
THE WAY OF A SHIP IN THE MIDST OF THE SEA;
And the way of a man with a maid
Proverbs 30, v.18, 19

Over the last 20 years or so science has much increased our understanding of the way of a ship in the sea.

Introduction

There are several ways in which the fighting capability of a surface warship is degraded in bad weather. Speed will be reduced, first by the increased resistance in waves and then, more rapidly, by a command decision that the motions are greater than the crew and equipments can stand, that slamming is endangering the structure or that wetness from green seas or spray has reached an unacceptable level. Helicopter operations and those of other weapon systems will be limited in bad weather, not necessarily in the same way as speed, whilst the use of towed arrays or minehunting sonars will pose yet another set of problems. In every example, the overall operating limit will take the form of a lower envelope curve embracing limits set by a number of individual parameters.

A warship is an integrated fighting machine which must retain its operational capability and mobility over as high a percentage of the year as possible.

History

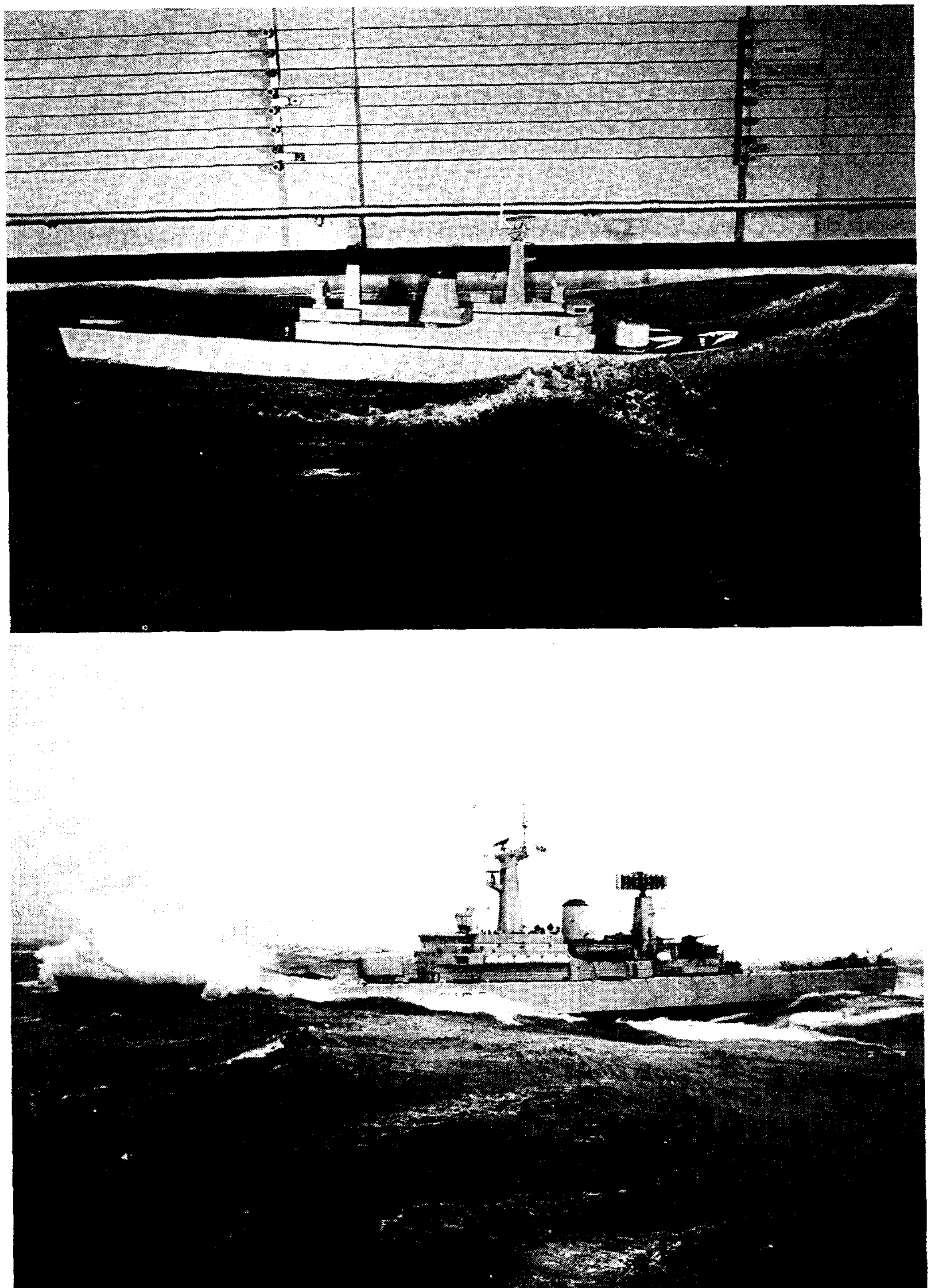
The development of sea kindly ships has always been an aim of the ship designer and in each era experience has led to the evolution of satisfactory solutions. Perhaps the first detailed study of the behaviour of warships in bad weather was that by the Torpedo Boat Destroyer Committee of 1903[1,2]. A detailed questionnaire was sent to the commanding officers of all destroyers and 73 replies were received and several captains were examined by the Committee. It was absolutely clear that the reputed 30 knots of these small vessels could only be reached in a dead calm sea and that by sea state 4 they were reduced to some 15 knots. The next class of destroyers, the RIVERS, had much more freeboard and a trial speed of 25 knots which could be used at sea.

The next great impetus for change came at the end of the second world war with the introduction of the Type XXI fast battery submarine. Two great Constructors N. G. Holt and Dr R. Gawn (AEW, Haslar), developed a family of frigates, WHITBY, etc., based to a considerable extent on Holt's experience as a yachtsman. The WHITBY, and the LEANDER, with the same lines, has gained a very high reputation in NATO as a sea boat and the form has been further developed in the BROADSWORD. The principal features of Holt's form were very fine lines forward with sharp V sections combined with high freeboard carried well aft and a bridge near amidships. The high freeboard meant that there was covered access fore and aft and the bridge was close to the point of least vertical motion. These two aspects ensured that the behaviour of the ship at sea felt good to the crew.

Up till a few years ago the only reliable way of proving a designer's ideas was by testing models (FIG. 2). In general, these could only be carried out in conventional ship tanks in head seas, though by 1960 AEW Haslar had a manoeuvring tank in which a model could run in any direction through a confused sea. Such tests were expensive and could only examine a limited range of parameters. Instrumented ship trials were much more expensive and even more limited in scope but were, and remain, essential to validate other methods.

The use of 'strip theory' for the prediction of ship motions is now well established and the results have generally been validated by ship trials[3]. Strip theory computes motion transfer functions for heave, pitch, roll, sway and yaw oscillatory motions, i.e. ship motion response to a sine wave excitation of unit amplitude or unit wave shape, depending on whether the motion is translational or rotational. Such transfer functions are evaluated at constant speed over a range of wave headings and frequencies of encounter. The extension of this approach to realistic, stochastic and multi-directional waves by St Denis and Pierson in 1953[4] using linear superposition made strip theory into a usable design tool.

Refining and proving the theory was not easy but it is now the primary means of studying motion and, for pitch and heave motions, fully meets the needs of the designer of ships and weapon systems. Roll motions have proved more difficult to handle due to problems in evaluating damping but papers



FIGS. 2A AND B—THESE TWO PHOTOGRAPHS SHOW A MODEL OF THE 'LEANDER' BEING TESTED AT ARE HASLAR COMPARED WITH THE SHIP HERSELF IN A SIMILAR SEA. AGREEMENT IS, PERHAPS, SURPRISINGLY GOOD

by Spouge[5] and others show that such calculations now put ships in the right order of merit and magnitude and can be used. There is still much to be done on the prediction of wetness and on structural loading from slamming but the main outstanding problem lies in setting acceptable criteria.

TABLE 1—*Relationship between wind speed and wave height*

					North Atlantic			North Pacific			Northern Hemisphere		
Sea State No.	Significant Wave Height m		Sustained Wind Speed* Knots		% Prob of Sea State	Modal Wave Period Sec		% Prob. of Sea State	Modal Wave Period Sec		% Prob of Sea State	Modal Wave Sec	
	Range	Mean	Range	Mean		Range**	Most Prob***		Range**	Most Prob***		Range**	Most Prob
0–1	0–0·1	0·05	0–6	3	0·70	—	—	1·30	—	—	1·00	—	—
2	0·1–0·5	0·3	7–10	8·5	6·80	3·3–12·8	7·5	6·40	5·1–14·9	6·3	6·60	4·2–13·8	6·9
3	0·5–1·25	0·88	11–16	13·5	23·70	5·0–14·8	7·5	15·50	5·3–16·1	7·5	19·60	5·1–15·4	7·5
4	1·25–2·5	1·88	17–21	19	27·80	6·1–15·2	8·8	31·60	6·1–17·2	8·8	29·70	6·1–16·2	8·8
5	2·5–4	3·25	22–27	24·5	20·64	8·3–15·5	9·7	20·94	7·7–17·8	9·7	20·79	7·2–16·6	9·7
6	4–6	5	28–47	37·5	13·15	9·8–16·2	12·4	15·03	10·0–18·7	12·4	14·09	9·9–17·4	12·4
7	6–9	7·5	48–55	51·5	6·05	11·8–18·5	15·0	7·00	11·7–19·8	15·0	6·82	11·7–19·2	15·0
8	9–14	11·5	56–63	59·5	1·11	14·2–18·6	16·4	1·56	14·5–21·5	16·4	1·34	14·4–20·0	16·4
9	14	14	63	63	0·05	18·0–23·7	20·0	0·07	16·4–22·5	20·0	0·06	17·2–23·1	20·0

* Ambient wind sustained at 19·5 m above surface to generate fully developed seas.
** Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.
*** Based on periods associated with central frequencies included in Hindcast Climatology.

PROCEDURE

The sections which follow will consider first the characteristics of the sea and then outline criteria which limit the performance of ships with their weapons and crew. The way in which seaworthiness is affected by different design parameters will be described and a procedure, shown diagrammatically in FIG. 3, outlined to compare the effectiveness of alternative forms.

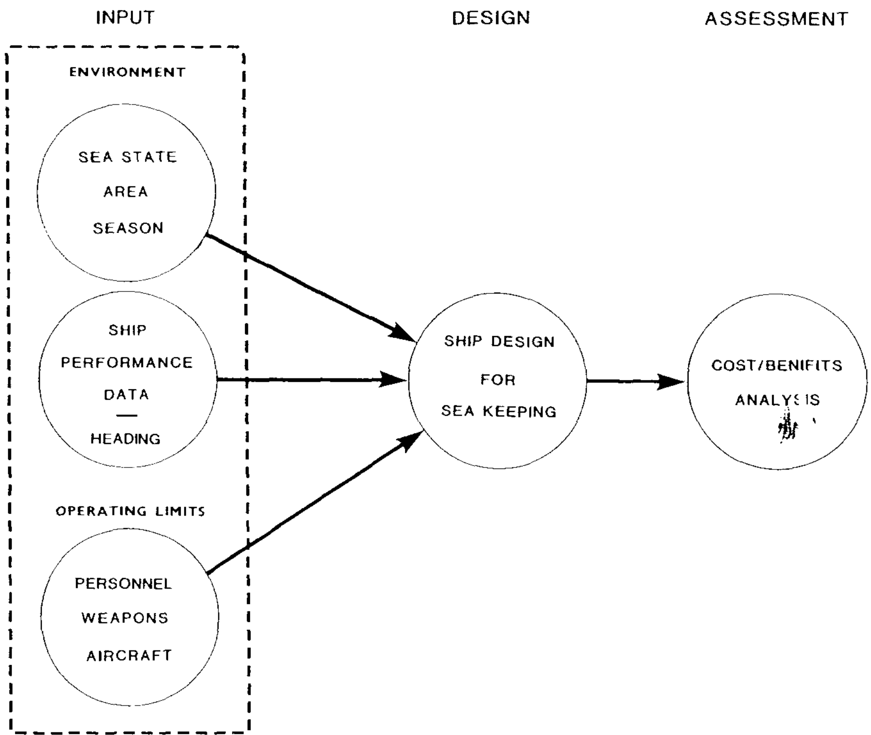


FIG. 3—SYSTEMATIC SEA KEEPING

The Environment

The sea is rarely calm, often rough and sometimes very rough. To quantify that statement is not easy since the description of a random sea requires many parameters to give a truly valid representation. For design purposes a simple description with either a single parameter (e.g. sea state) or at most two (wave period or length and height) will be necessary.

The effect of wind must be considered as well as that of waves. When a wind blows steadily for a considerable time there is a relationship between wind speed and wave height given in TABLE I. In coastal waters there may well be insufficient fetch for the wind to generate steady state waves. In such areas a given wave height corresponds to a higher wind speed, which has importance when considering air-driven craft such as hovercraft.

There are many different published relationships between sea state, wave height and period. That given in TABLE I is taken from STANAG 4194 which has been ratified by the U.K. and will be used in future. Older definitions varied, sometimes quite considerably, between different eras and different countries. Older data were mainly subjective but more recently satellite photography has been used to produce more reliable figures.

It may be important to define the area of operation more closely. For example, sea conditions at weather station INDIA are considerably more severe than those averaged over the whole North Atlantic. Similarly, it is necessary to be precise as to the seasonal variation; for some cases an average of the year may be appropriate whilst in other cases it may be useful to consider extreme winter conditions (see FIG. 4).

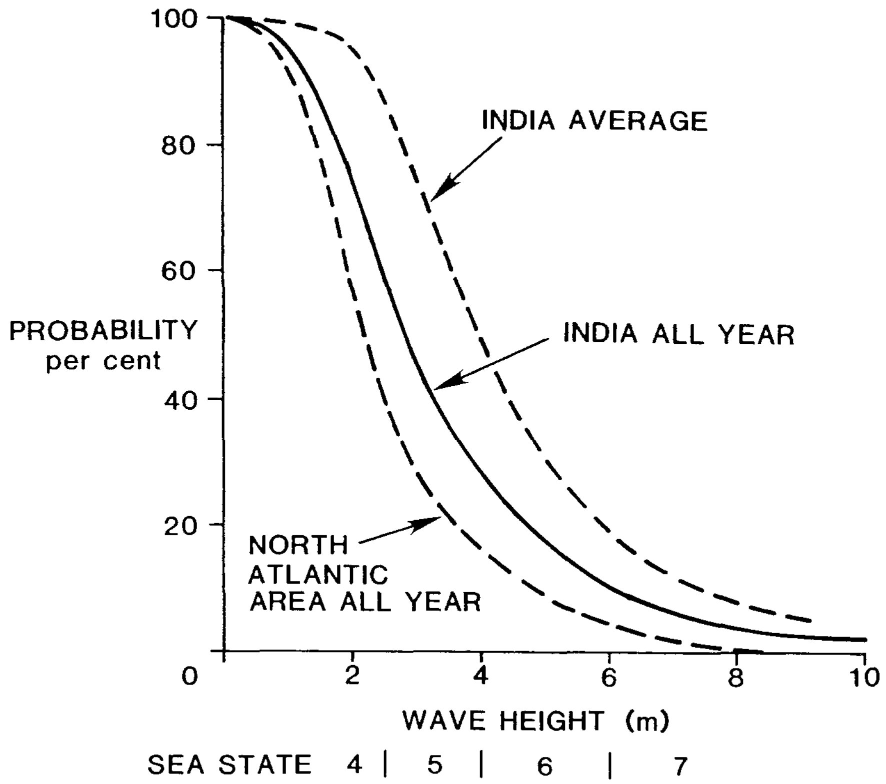


FIG. 4—PROBABILITY OF EXCEEDING A GIVEN WAVE HEIGHT
UPPER LINE: WEATHER STATION INDIA, WINTER
CENTRE LINE: WEATHER STATION INDIA, AVERAGE OVER THE YEAR
LOWER LINE: WHOLE N. ATLANTIC AREA, AVERAGE OVER THE YEAR

The severity of the apparent wave patterns encountered by a ship depends on its heading and if the Captain is free to alter course he can do much to reduce the effects of bad weather. For example, the percentage of time in which helicopter operation is possible is much greater if the ship is free to choose the optimum course. On the other hand, towed array ships are often constrained to follow a given course and speed and must put up with the ensuing motions.

Components of Motion

It is customary to represent the motion of a ship in a sea way in terms of the following components:

Angular	*Linear*
pitch	heave
roll	sway
yaw	surge

Each of these components has amplitude, velocity and acceleration and any one of the resulting 18 parameters and many combinations of them may be of concern. Some degree of simplification is essential but each such simplification reduces the validity of the statement; it is essential to appreciate the significance of all assumptions made.

The usual simplifications are:

(*a*) Neglect sway and surge. (Sway can contribute significantly to lateral acceleration).

(*b*) Neglect yaw except in association with broaching.

(*c*) For design, consider pitch and heave in head seas and roll in beam seas.

These assumptions may be very useful in the early stages of a design but should be replaced as soon as possible. Vertical motions (the combination of pitch and heave) in *head* seas are important and easy to study in a conventional ship tank. However, heave is slightly greater in *beam* seas. Similarly, it may be convenient to consider rolling in beam seas even though peak motions occur with seas a little off the beam.

Particular care is needed to identify the relative importance of amplitude, velocity and acceleration. In particular, human senses tend to interpret lateral *acceleration* as an apparent roll *angle* and hence reported roll angles usually contain an appreciable acceleration term and exceed the true amplitude. The effect of heading on ship motions is conveniently shown as a polar plot in which a motion, such as roll, is plotted or in which a contour is drawn showing exceedence of an operating criterion (FIG. 5).

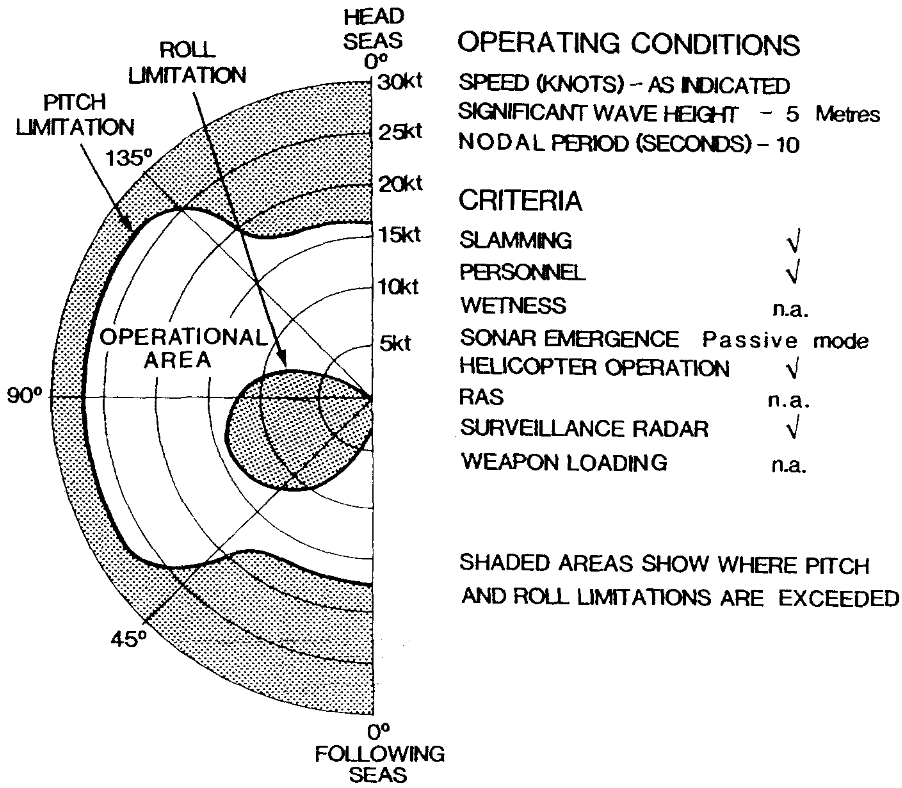


FIG. 5—LIMITING MOTION CONTOURS

Operating Limits

The operating limit of a ship or ship system is set by the lower bound of a number of individual limiting curves (FIG. 6). For example, the speed of a ship in rough weather is reduced first by the added drag of seas and then further reduced by a command decision that motion, slamming or wetness are likely to cause damage or unacceptable degradation in crew performance.

The effect of slamming on frigates is to increase the overall bending moment on the ship by some 25% over a quasi static loading and to move the maximum stress to a point well forward of amidships[6]. There is, of course, severe local panel loading forward. Immediate structural failure from wave loading is unlikely (less than 1 chance in 100 years) but the increased loads are reflected in a reduction of fatigue life and an earlier onset of cracking at stress concentrations. The constraints of towed array operations lead to significantly increased structural loading, sometimes in unusual modes; e.g. torsional.

The shipping of green seas can also cause damage to weapons, fittings and the fore end of superstructures. Wetness, due to salt spray or green seas, will cause corrosion problems and may obstruct vision. Water on oily and rubber impregnated decks can lead to a loss of grip which can be a hazard to men and helicopters, particularly if associated with high lateral accelerations.

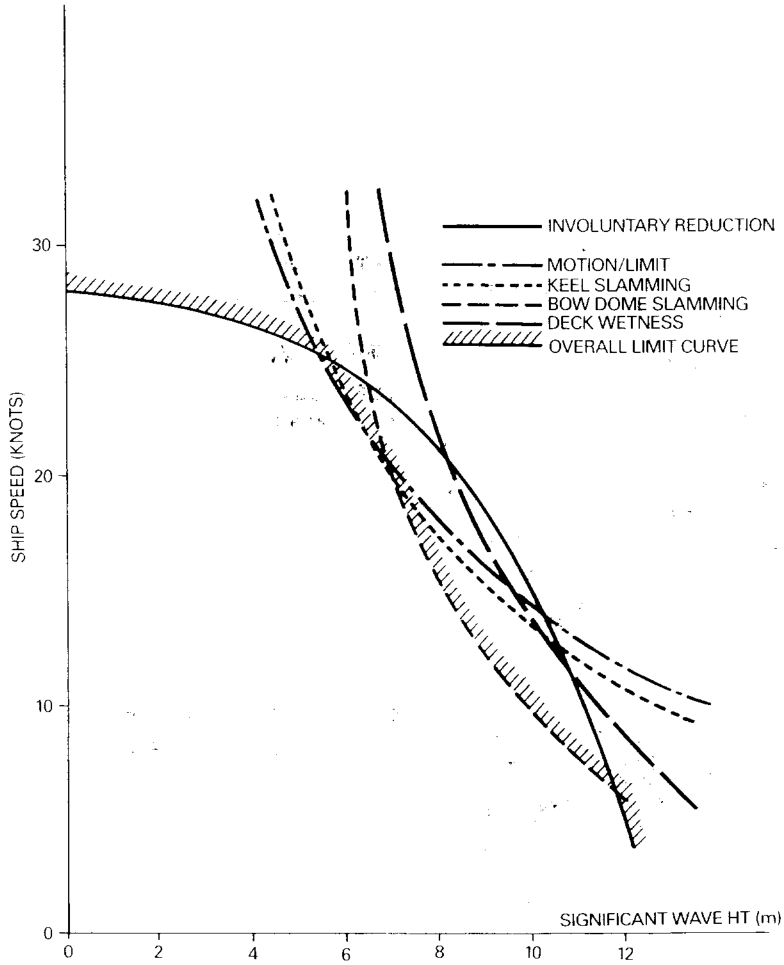


FIG. 6—HEAD SEA LIMITATIONS

People

Men vary considerably in their response to motion and any one man will respond differently from one occasion to another. Human reaction depends not only on what is happening *now* but on what has happened *previously*—e.g. when was the last meal, how tired is the man, etc., as well as on the extent to which the man is accustomed to motion.

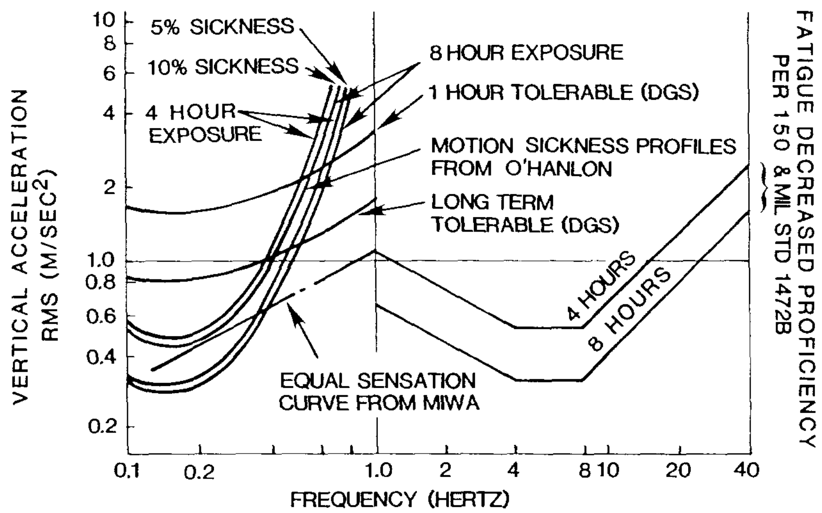


FIG. 7—ACCELERATION LIMITS FOR PERSONNEL

The degradation of human performance is normally split into short and long term effects and the curves below are of use in the early stages. The 'DGS' 1 hour curve (FIG. 7) is based on the results of questionnaires in the R.N. on what is acceptable in peacetime. In emergency, much higher levels of motion can be accepted though the degree to which performance is affected is unclear[7]. The longer term curve is also based on peacetime acceptability but is consistent with evidence from World War II[8].

An approach which allows for the effects of frequency as well as motions uses subjective motion magnitude (SMM)[9] (see Appendix I, p. 33). Experience suggests[10] that captains will take action to reduce motions if the SMM is above 12. More tentatively, it has been suggested[13] that the SMM averaged over the year should not exceed 4.

The designer's objective is to reduce motion to a level at which crew performance is adequate. Degradation of human performance can be due to:

(*a*) Nausea.

(*b*) Loss of sleep, exhaustion, etc., affecting judgement.

(*c*) The need to hang on.

Of these (*b*) is insidious, as judgement may deteriorate without the victim realizing it.

Sickness is thought to be caused by vertical acceleration, the sum of that caused by pitch and heave, though susceptibility to illness can be increased by tiredness (effect of roll, etc.). Nausea is a highly tuned response, and is most likely with motion frequencies between 0·15 and 0·30 Hz, frequencies only too likely to occur in the motions of medium sized ships.

Exhaustion can be caused by any prolonged motion, though roll (lateral acceleration) is a particularly important influence. Noise, vibration, cold (as on open bridges) can all add to exhaustion and lead to impaired judgment[7].

The old saying 'One hand for yourself and one for the ship' emphasizes the sheer difficulty of hanging on in a ship in rough weather. Baitis *et al.*[11] investigated helicopter deck operations on an FFG7 frigate using time and motion methods. The procedure was simulated using generated time histories of the motions combined with a mathematical model of a man standing and walking. Lateral acceleration levels causing a loss of balance—stumbles—were identified from a range of sea states; speeds and headings and the following risk levels of lateral accelerations were identified in terms of possible stumbles or 'Motion Induced Interruptions' (MII) (see TABLE II and Appendix II). These figures are consistent with the more general rolling criterion proposed by Monk, discussed later.

TABLE II—*Lateral Force Estimator*

	Lateral accln g	*MII*	*Risk*
Level 1	0·08	One MII per 18 evolutions	
2	0·10	One MII per 2 evolutions	
3	0·12	1·4 MII per 2 evolutions	serious
4	0·14	2·6 MII per 2 evolutions	severe
5	0·16	4·0 MII per 2 evolutions	extremely hazardous

MII: Motion Induced Interruption

Roll forces are particularly important in ships carrying aircraft. The coefficient of friction between deformable surfaces (tyres) and rough, abrasive surfaces is complicated and depends on loading and relative speed. The search for a flight deck paint which provides good friction characteristics, even when soaked in oil, wet and dry, which can withstand packing cases dragged across it and may also serve for deck hockey, is unending and difficult.

Weapon System, Helicopter Operations, etc.

Dr Lloyd[12] has outlined the criteria for helicopter operation in considerable detail. The task can be divided into following aspects:

- Routine maintenance
- Preparation for flying
- Ranging on deck
- Spreading and folding rotors
- Refuelling
- Re-arming
- Take off and landing.

All these operations are governed by different criteria of motion and wind strength and direction, often involving the ability of the crew to carry out the work.

Key motion attributes are:

- Vertical velocity
- Roll angle
- Vertical and lateral acceleration
- Wind speed and direction.

Whilst advantage can be taken of 'quiescent periods' even in quite severe sea states, it is clear that helicopter availability in bad weather is increased if motions are reduced. Moving the landing spot closer to amidships is an effective way of reducing motions (FIG. 8), though hard to achieve in practice.

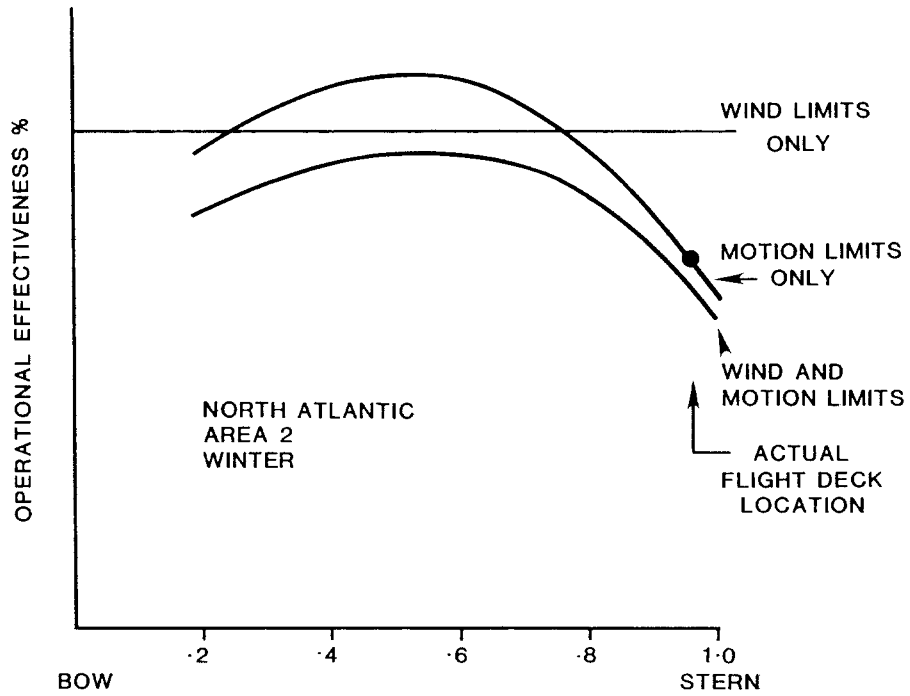


FIG. 8—EFFECT OF FLIGHT DECK POSITION ON OPERATIONAL EFFECTIVENESS

The performance of any other weapon system can, in principle, be assessed in a manner similar to that given above for helicopters, though published data are rare. FIG. 9 gives some indication of the hit probability of a medium calibre gun on a moving platform.

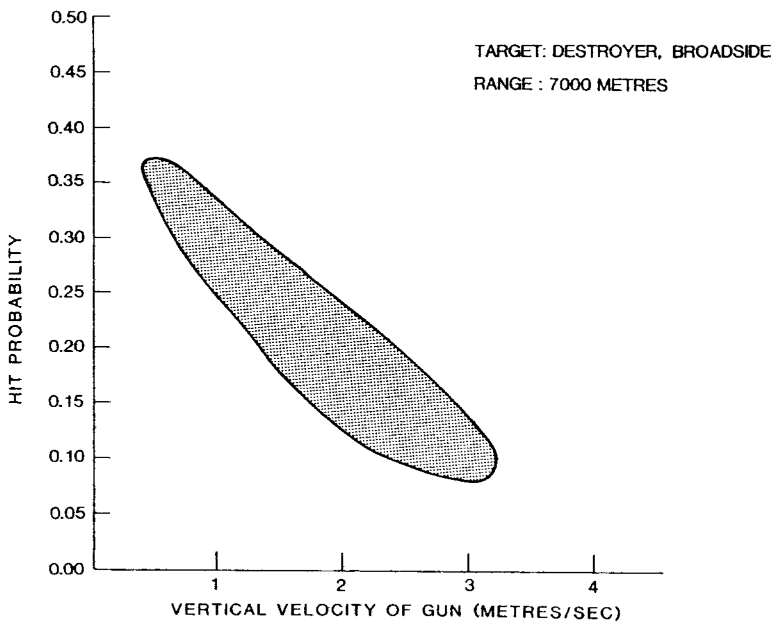


FIG. 9—HIT PROBABILITY V. GUN MOUNT VERTICAL VELOCITY

DESIGN FOR SEAKEEPING

The starting point, as in all design tasks, is to define the problem. The Staff and the constructor must be quite clear as to the primary role and its requirements for seakeeping. The requirement may be maximum speed in a sea way, ability to operate helicopters in high sea states or the use of a towed array at low speeds. The operational requirements must then be redefined in technical terms such as limits on roll amplitude, lateral force, SMM, MII, vertical acceleration etc. In many cases, there will be multiple limits and a 'cure' for the worst will expose another limit only a little less severe. In particular, the effectiveness of smaller ships (under 100 m length) is likely to be controlled by human factors. Wind, too, can be a limiting factor in its own right.

Design Approach

There are two ways in which the design (synthesis) task may be accomplished:

(*a*) The systems approach, in which specified criteria are set out and the ship designed to meet them (Fig. 10).

(*b*) The comparative approach in which the requirement is that the new ship should be as good as, or slightly better than a ship in service.

Philosophically, (*a*) is the better approach but well founded criteria are often missing and a combined approach may be used.

Such criteria as do exist often prove, on closer examination, to relate only to specific ship types in a particular operating mode. Most such criteria tend to imply a frigate sized ship with a roll period of 10–12 seconds in which apparent roll angle may be used as an approximation to acceleration. One fairly consistent set, for sonar operation, is given in Table III.

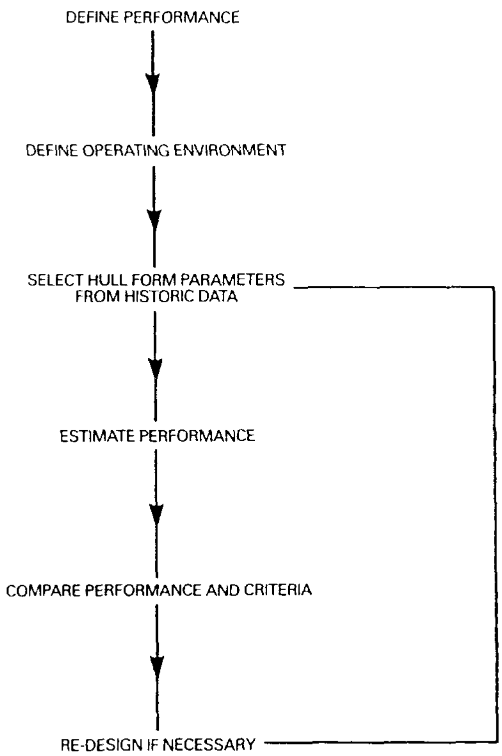


Fig. 10—The systems approach for design

The design of the Castle Class OPV[13] is a case in which a combination of both approaches was used. It was clear from the start of design work that motions must be at an acceptable level for long periods and that there should be no serious degradation of performance in any weather in which fishing was possible.

Table III—*Typical criteria for sonar operation in a frigate*

	Displacement m	*Velocity* m/s	*Frequency* per hour
Slamming	5	4	20
Wetness	7·5	—	30
Sonar emergence	5	—	80

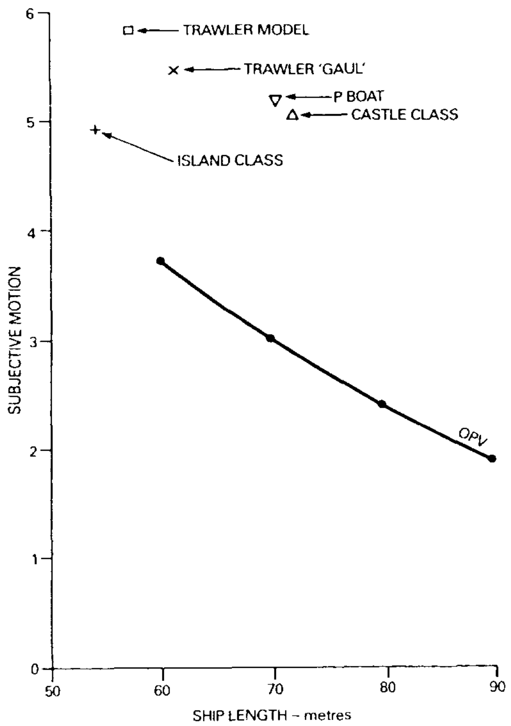


FIG. 11—
AVERAGED SUBJECTIVE MOTION MAGNITUDE V. SHIP LENGTH. STATION INDIA, NORTHERN NORTH ATLANTIC
Reproduced by courtesy of R.I.N.A.

From historical data it was decided that a length of about 80 m was needed to reduce pitch and heave to acceptable values. Marshall at the Admiralty Research Establishment, Haslar, then computed these motions for a number of variants of the design with lengths between 60 and 90 metres, together with similar figures for a number of existing ships. The environment was represented by two sets of scatter diagrams giving the frequency of occurrence of waves of different lengths and periods at two locations. Motions were computed for each sea state and a weighted annual average obtained which was converted into subjective motion magnitude. The SMM was then averaged over the length of the ship occupied by living and working spaces (FIG. 11). A length of 75 metres was then selected as significantly better than the ISLAND Class which were thought to be a bit unpleasant. The resulting CASTLE Class has been very favourably reported on both in normal operation and during the Falklands war[14].

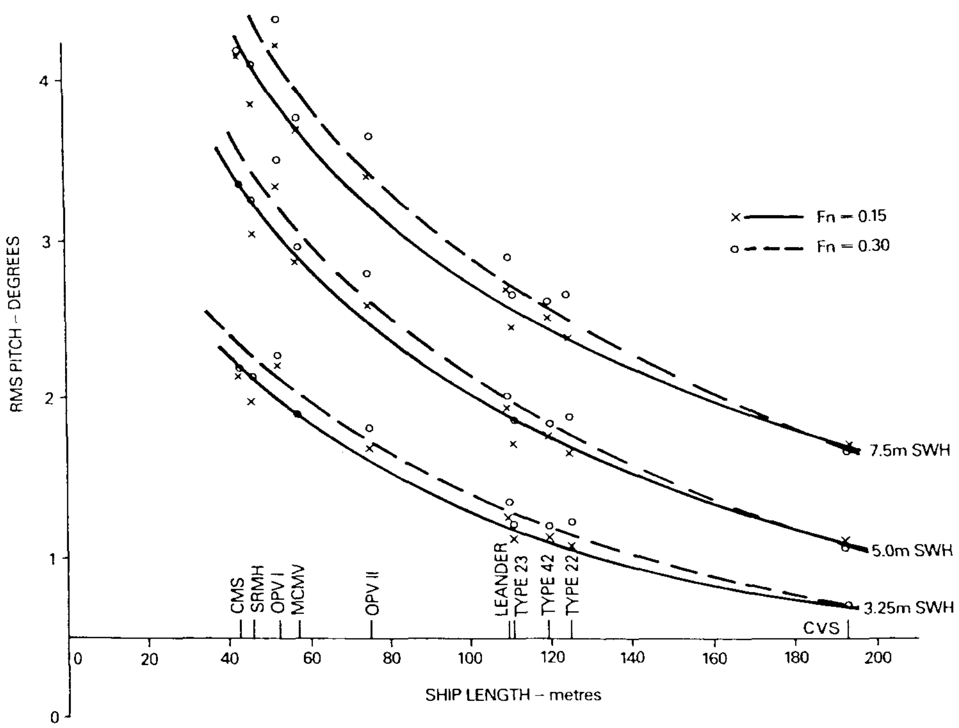


FIG. 12—RMS PITCH ANGLE (MAX. VALUES): FUNCTION OF LENGTH, SEA STATE AND SPEED. 'GODDESS' COMPUTED RESULTS. ITTC SPECTRA

The Effect of Varying Dimensions on Motion

Length

Increase in length will always reduce pitch and heave motions, and hence vertical accelerations, in head seas. The benefits are non-linear (FIG. 12), with the greatest effect seen in shorter ships. Subjective motion is also reduced by increase in length as shown in the design of the CASTLE Class. The relative motion between stem and wave crest increases with length which is why freeboard and draught must be increased in longer ships.

The value of reducing motions can be calculated by evaluating the number of days in which the relevant criteria are exceeded. Taking a notational value of £100,000 for the cost of one frigate-day at sea, it can be shown that increasing the length of a frigate from 108 metres to 125 metres reduces the number of days operation lost per year from an equivalent of 12 to 7 with an imputed benefit of £500,000 per annum[15].

Beam

The beam of a ship directly affects the metacentric height and hence both the stability (resistance to heel) and the rolling characteristics. In consequence, selection of beam implies a nice balance between adequate stability and

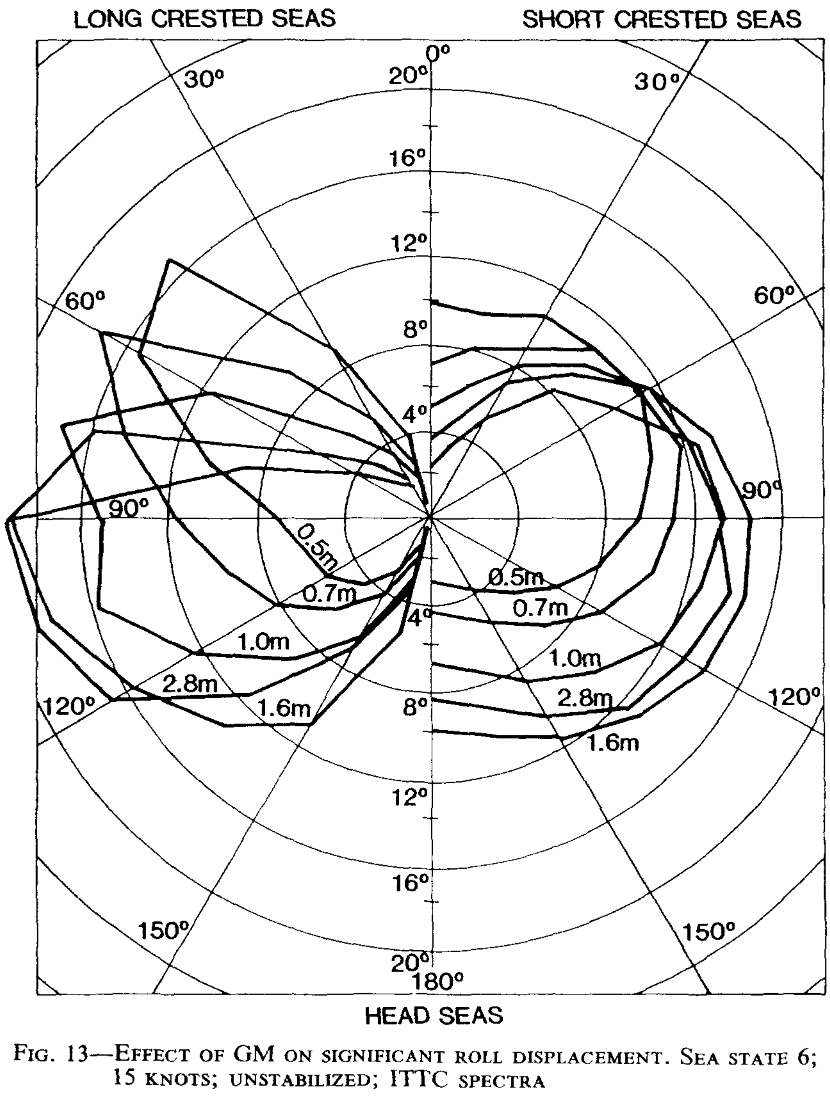


FIG. 13—EFFECT OF GM ON SIGNIFICANT ROLL DISPLACEMENT. SEA STATE 6; 15 KNOTS; UNSTABILIZED; ITTC SPECTRA

avoiding excessive stiffness with unacceptably rapid rolling. Excessive beam/draught ratios (over 4·5) lead to a rapid increase in resistance.

Effect of metacentric height. Changes in metacentric height (GM) will affect roll period, the heading at which the most severe rolling occurs, the roll amplitude and roll acceleration. FIGS. 13 and 14 show the results of computer studies in which the metacentric height of a LEANDER Class frigate was arbitrarily varied at constant beam. It will be seen that at low GM (long period) the worst rolling is in quartering seas while at high GMs seas forward of the beam are worst. The maximum roll amplitude does not vary greatly with GM though short periods do lead to somewhat greater rolls. However, short period (high GM) ships will always have much higher roll accelerations. Results are shown for both long and short crested seas over a range of sea states.

Bilge keels, stabilizers, etc. Bilge keels add greatly to the damping of roll and are effective at all speeds (the effect does increase with speed). Only very recently has it been possible to set out technical requirements in terms of lateral force estimator (LFE) and hence it has been all too common for the bilge keels to be found inadequate as built. There are practical difficulties in fitting big bilge keels as they must be within the envelope of the ships side and bottom for ease in coming alongside and docking.

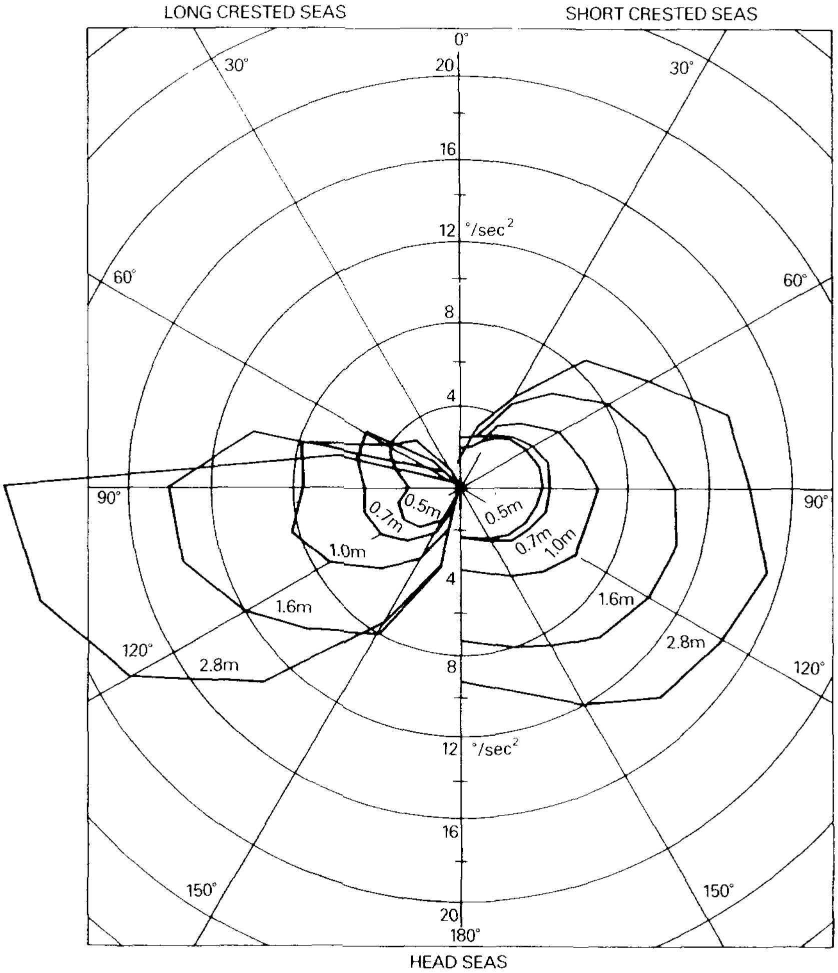


FIG. 14—EFFECT OF GM ON SIGNIFICANT ROLL ACCELERATION. SEA STATE 6; 15 KNOTS; UNSTABILIZED; ITTC SPECTRA

The keels must not extend too far forward or they will be damaged when the ship slams and, in order to minimize noise and vibration, they usually cannot be fitted abaft stabilizer fins. Big bilge keels will also add to drag and cause a loss of speed. (The ISLANDS lost about ½ knot when their bilge keels were enlarged).

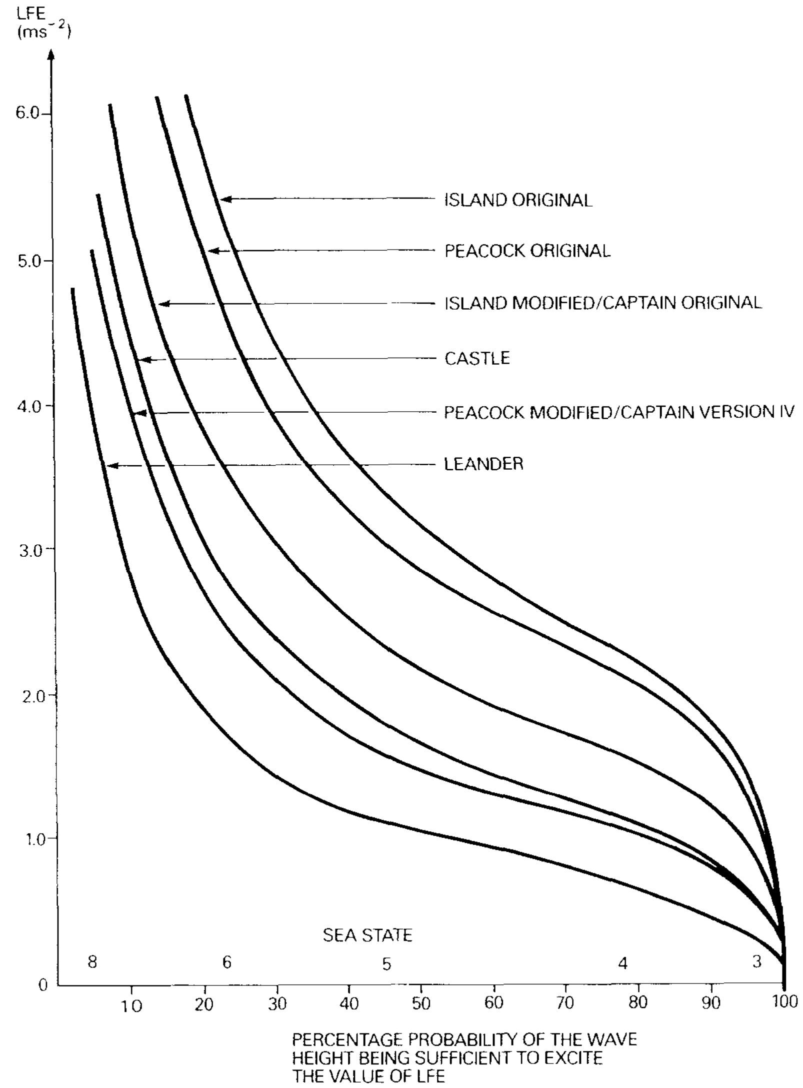


FIG. 15—CALCULATED LATERAL FORCE ESTIMATOR

In 1986 K. Monk proposed the following approach in a M.Sc. dissertation at University College London. He took note of three classes of ship in which the rolling characteristics had been found so unacceptable as built that the ships were altered to have bigger bilge keels and, in some cases, changes to GM and to polar moment of inertia. The ships concerned were the current ISLAND and PEACOCK Classes and the World War II CAPTAIN Class frigates. Monk compared computed values of motion and damping with subjective reports, before and after modification and with AEW model tests of the CAPTAIN Class. He showed that the lateral force estimator (FIG. 15) matched well with these reports. The lateral force estimator is derived in Appendix II; in simple terms it is the combined force parallel to the deck due to roll acceleration and to the resolved gravitational force at maximum amplitude.

The LFE is calculated

on the worst heading,

in a short crested ITTC 2 parametric spectrum (Cosine squared spreading function),

at 5 knots,

on the bridge.

Under these conditions the LFE should not exceed $1 \cdot 5\ \mathrm{ms}^{-2}$ in mid sea state 5. Further work by the Chief Naval Architect's staff has shown that this approach gives results consistent with reports from sea for ships ranging from the TON Class to the CVS and large RFA. It is intended to introduce this level of LFE as a Naval Engineering Standard.

Active fin stabilizers are very effective in reducing roll at speeds above about 8 knots. First introduced into the R.N. in 1936 (sloop *Bittern*) and perfected about 1950, they are now fitted to most British warships. High aspect ratio, retractable fins (as in the TRIBAL Class) are most efficient but the demands on weight and internal space were found excessive and the fixed fin is now universal. Model tests and a few ship trials have been carried out using the rudder as a stabilizer. Whilst some success was achieved, the development of a totally reliable and effective system to carry out two different and vital tasks has been seen as too difficult. Tank stabilizers are fitted in a few ships. They have not been found very effective but may be the only solution for low speed operation.

The differing performance of bilge keels and active fins can cause problems when the role of a ship is changed. For example, the Batch I Type 22s had two pairs of fins and a relatively small bilge keel which controlled rolling very well at moderate to high speed. The Batch IIs had the same fit but when operating at low speeds with towed array the fins are effective and a bigger bilge keel, perhaps with only one pair of fins, might be better.

Draught

The choice of draught is affected by requirements for sonar immersion, propeller diameter and frequency of slamming. For the smaller vessel, slamming requirements are likely to be the most important. FIG. 16 gives an indication of the draught needed to maintain a given speed in different sea states based on reports from sea and computed values. Though the scatter, indicated by the shaded area for sea state 6, is considerable, the trend is clear.

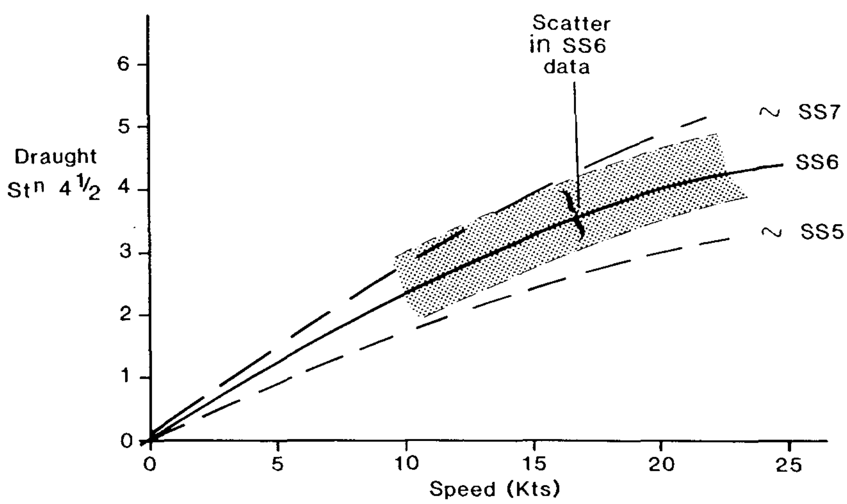


FIG. 16—SLAM LIMITING SPEEDS

Waterplane Area, etc.

Work by Schmitke and Murdey[16,17], supported by unpublished work by Lloyd at Haslar, has demonstrated the value, in reducing pitch and heave motions, of:

- increasing waterplane area coefficient, particularly forward;
- reducing block coefficient;
- using V sections forward.

Individually, the effects are not large but the cumulative effect of getting it all right may be appreciable. A high beam/draught ratio will also reduce pitch and heave but it is likely that beam and draught will already be chosen on other factors.

Above Water Form

Green seas will sweep over the bow if the resultant amplitude of pitch and heave puts the stem head below the wave surface, as distorted by the pressure field of the ship. Reduction of pitch and heave (relative bow motion) is a first step towards a dry ship but a high freeboard is the most important factor. As in all design, excess is to be avoided: too high a freeboard will make the centre of gravity unacceptably high and, particularly forward, can lead to handling problems in strong winds.

The required freeboard is governed by length, with smaller ships requiring a *relatively* greater freeboard. Since World War II there has been a tendency in most nations to increase freeboard, reflecting an awareness of the need to be effective in all weathers. A good working rule is that

$$\text{freeboard at bow} = 0{\cdot}6\sqrt{L}\ \text{metres}.$$

This is likely to correspond to about 100 'wettings'/hour. Faster ships should have increased freeboard. Freeboard aft can be important if winches, etc., have to be worked at sea and, tentatively, a height of $0{\cdot}35\sqrt{L}$ metres is suggested. A helicopter deck must be dry in order to retain an acceptable coefficient of friction and a height of 4·5 to 5·0 m is desirable. Such approximations are confirmed by computations and model tests for individual designs.

Bulwarks provide a relatively cheap way of increasing freeboard though care is needed to ensure that a large mass of water is not entrapped causing loss of stability. A continuous freeing port is recommended and deck areas with bulwarks should be open at the after end.

Bow Shape

The rake of the bow should be considerable with an overhang of 5 to 7% of the length. The effect of flare and of knuckles is still a matter of debate. Lloyd[18] has shown that a relatively small flare reduces the wetness due to green seas in head seas though the effect is not great. It is not clear whether or not flare and knuckles are effective in keeping spray clear of the ship. Hard facts are rare and emotions run high[19]. It is clear that slamming can take place under excessive flare and also that a knuckle which is set too low can generate spray. A knuckle height of about $0{\cdot}35\sqrt{L}$ seems to be the lowest effective position. Evidence on the effectiveness of spray deflectors is even less clear. Whilst a well-positioned deflector can be effective in a particular sea state, another, in different conditions may make matters worse.

Attention to detail is important. Too blunt a stem can cause a breaking bow wave with showers of spray. Overlapping plates, badly positioned anchors, etc., can all be the cause of a wet ship.

The Value of Improved Seaworthiness

The value of different aspects of seaworthiness has been touched on in earlier paragraphs and an attempt is made in this paragraph to bring these together.

The fighting capability of a frigate is limited by bad weather, TABLE IV[15], giving a simple indication of the overall effect of rough sea on fighting capability that has been agreed with the Directorate of Naval Warfare. These percentages are envelope figures taking into account loss of efficiency of the crew and of individual weapon systems and the helicopter. These figures relate to the ability to fight *now*. Obviously, a frigate labouring in sea state 8 has potential value from being on station to fight when the sea moderates.

In the North Atlantic, a LEANDER will lose the equivalent of 15 days operational capability due to bad weather in the course of a year.

TABLE IV—*Effect of rough sea on fighting capability*

Sea State	*% loss of fighting capability*
0-4	0
5	10
6	30
7 & over	95

Over and above these large but indirect losses there are direct consequences of poor seaworthiness; missiles lost or damaged on the forecastle, helicopter accidents and the insidious loss of fatigue life in the hull leading to very expensive repairs. Finally, it may be that life on the rolling sea is a factor in persuading sailors not to re-engage.

What can be Done?

The simplest answer is to make ships bigger. A big ship will always behave better in random seas than a small one. The cost of enlarging a design for improved seakeeping is small in relation to operational benefits. In the example quoted earlier a comparison was made between a 108 metre and a 125 metre design. A balance sheet has been drawn up in TABLE V.

TABLE V—*Gain or loss for larger ships*

Gain in operational effectiveness at £100K/day = £500,000 p.a., discounted at 10% over 20 years	+ £4 250 000
Reduced fuel consumption of larger ships, discounted at 10%	750 000
Total benefit	£5 000 000
Cost of the larger hull	2 000 000
Net gain for bigger ships	£3 000 000

There are still gains to be achieved by fine tuning of section shapes, waterplane area, bilge keel size, etc. The Type 23 will have most of these benefits and further great advances are unlikely. However, such benefits are not automatic and self-perpetuating and continual effort by designers and research workers at Haslar is essential to maintain the standard.

The next step forward is the SWATH. The U.S. Navy has recently ordered T-AGOS 91 which is a SWATH, and model tests suggest that she will retain operational capability in sea state 8. There are strong indications that the production costs of a SWATH are little greater than for a corresponding monohull, but SWATH must be the subject of a later article.

The sea is unchanging; it can indeed be cruel and the statistics of extremes can lead to some unpleasant surprises. On the other hand our knowledge of what can be done to give improved seaworthiness is considerable and our ability to assess the value of such improvements is necessary.

Acknowledgement

The author is very conscious that almost all his knowledge of seakeeping has come from discussions with Dr Adrian Lloyd, ARE Haslar, over many years.

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An excellent survey of the underlying science is contained in:

Cox, G. G.: Seagoing qualities of ships; *Proc. International Seminar on Ship Weather Routing, Tokyo, December 1987.*

NOTE: The author would be very grateful for photographs or ciné-film of warships, British or foreign in high sea states (5 or over); in particular for sequences showing a whole period of pitch or heave. Any such photos should be sent to DCNA, Room 55, Block F, Foxhill, Bath, with a note of estimated sea state, wind speed, course relative to wind and sea and any notes on operational limits at the time.

APPENDIX I—SUBJECTIVE MOTION

Schoenberger's work[9] has been used by Lloyd & Andrew[10] to define acceptable limits of vertical acceleration. Schoenberger subjected a sample population of U.S.A.F. pilots to vertical sinusoidal motions to identify the combination of acceleration and frequency which gave equal subjective impression. An arbitrary linear scale of subjective motion magnitude (SM) was devised in which a control motion was defined as magnitude 10 and a motion which felt twice as bad defined as 20.

It was shown that a power law relationship of the form

$$SM = A(f)(\ddot{s}/g)^{1 \cdot 43}$$

seemed to fit the results obtained where

$$A(f) = 30 + 13 \cdot 53(\log_e F)^2$$

($\ddot{s}$ is vertical acceleration; g the acceleration due to gravity; F the harmonic frequency).

Assuming that shipborne personnel are chiefly influenced by the significant features of a ship's random motion, we may express the SM at any point in the ship in terms of m4 (the variance of absolute acceleration at this point) and m6 (the rate of change of the latter).

$$i.e.\ SM = \left[3 \cdot 087 + 1 \cdot 392 \left(\log_e \frac{1}{2\pi} \sqrt{\frac{m_6}{m_4}} \right)^2 \right] m_4^{0 \cdot 715}$$

Hence knowing the absolute motion variances at a point in a ship we can determine the corresponding value of the subjective motion.

Motion Weighting

Subjective motion varies along the length of the ship and it is necessary to apply a simple weighting function to the SM values calculated for each point in the ship and average the result. It is usual to take unit weighting over the living and working spaces of the ship and zero elsewhere.

Application of SM to Ships from about 50 m to 90 m long (BP)

Experience so far gained in applying the formula

$$SM = A(f) \frac{\ddot{s}}{g}^{1 \cdot 43}$$

to ships from about 50 m to 90 m LBP has shown that:

(*a*) the variation of 'weighted' SM across a scatter diagram is mainly due to the variation of $\ddot{s}$ (the vertical acceleration). The variation of the function A(f) is apparently of second order compared with $\ddot{s}$,

(*b*) the variation of 'weighted' SM between different forms is again mainly due to the variation of $\ddot{s}$.

These findings apply to ship motions calculated in both JONSWAP and ITTC two-parameter spectra.

In other words, the difference in the calculated subjective motion values for a given ship and between different ships is mainly due to the differences in the calculated vertical acceleration.

APPENDIX II—APPARENT FORCES AND ACCELERATIONS EXPERIENCED BY AN OBJECT ON THE DECK OF A MOVING SHIP

Consider an object of mass m tonnes on the deck of a moving ship. Suppose that the horizontal and vertical accelerations of the centre of gravity of the object are y m/sec^2 to starboard and z m/sec^2 downwards in a frame of reference fixed with respect to the earth. Then the accelerations in the plane of the deck and normal to the deck are

$y \cos\phi + z \sin\phi$ m/sec^2 to starboard

and

$z \cos\phi - y \sin\phi$ m/sec^2 downwards

These accelerations will tend to topple or slide the object to port and to lift it off the deck. Their effects may therefore be represented by two apparent forces:

$m(y \cos\phi + z \sin\phi)$ kN in the plane of the deck to port

and

$m(z \cos\phi - y \sin\phi)$ kN upwards normal to the deck.

In addition there are contributions from changes in the compartment of gravity due to the ship's roll angle. In the plane of the deck the gravity component is

$mg \sin\phi$ kN to starboard.

When the ship is upright the gravity component normal to the deck is

mg kN downwards

and when the ship is rolled this becomes

$mg \cos\phi$ kN downwards

So the roll angle reduces the downward gravity component by an amount

$mg (1 - \cos\phi)$ kN

So the total apparent forces on the object are

$m (y \cos\phi + z \sin\phi - g\sin\phi)$ kN

in the plane of the deck to port and

$m (z \cos\phi - y \sin\phi + g(1 - \cos\phi))$ kN

upwards normal to the deck.

Hence the apparent accelerations as perceived by the object are

$y_a = y \cos\phi + z \sin\phi - g \sin\phi$ m/sec^2

in the plane of the deck to starboard and

$z_a = z \cos\phi - y \sin\phi + g(1 - \cos\phi)$ m/sec^2

downwards normal to the deck.

For small motions these reduce to

$y_a = y - g\phi$ m/sec^2 in the plane of the deck to starboard

$z_a = z$ m/sec^2 downwards normal to the deck.