PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Seakeeping [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1991 **334**, 253-264
doi: 10.1098/rsta.1991.0012

Seakeeping

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It is well known that ship performance is degraded in rough weather. In moderately severe conditions every task on board the ship will take longer than it does in calm weather. The passengers and crew may be seasick and they will have to take more care when moving around the ship to avoid injury. The physical performance of mechanical and electrical systems may also be reduced if the ship motions are severe. Cargo may be damaged and this may also be considered as a reduction in performance. In extreme conditions, the ship may capsize or founder and this is, of course, the ultimate loss of performance.

The aim of research in seakeeping is, or should be, to develop techniques of predicting the degradation of performance a ship will experience in rough weather. If this can be achieved it will enable the ship designer to eliminate unsatisfactory and unsafe ships at an early stage in the design process.

The paper begins by summarizing the standard techniques for predicting the motions a ship will experience in rough weather. These are based on well-known strip theories coupled with superposition techniques for inferring the statistics of the motions in irregular waves from the regular wave transfer functions.

These techniques are quite well validated for conventional monohull ship motions in the vertical plane but predictions of motions in the lateral plane are rather less reliable and further work is needed in this area.

Accurate predictions of the irregular motions in realistic sea states are only one step in achieving the ultimate goal of predicting the rough-weather performance of new designs of ships. We also need to estimate the maximum permissible levels of the motions (usually known as seakeeping criteria). There are, in principle, no universally applicable criteria. They depend on the activities within the ship while it is engaged in a given mission and also on the type of equipment used. We therefore need to quantify the way in which the performance of the various sub systems or tasks which make up the ship mission degrade in rough weather. Ideally the first step should be to examine each task (or at least a representative selection of the important tasks) and to study the way in which the performance degrades. This will allow the motions (or other rough-weather phenomena) which are important for that particular task to be identified. It is then necessary to determine the maximum permissible levels of these motions by simulation, questionnaires, trials or even guesswork.

Finally there is a need to develop universally acceptable measures of performance. Ideally these might include elements of the time required to complete a task (in relation to the time required in calm weather) as well as the quality of the result.

1. Introduction

For many years ships were designed for optimum performance in calm water (best speed and lowest fuel consumption). This is well illustrated by considering the typical

Phil. Trans. R. Soc. Lond. A (1991) **334**, 253–264
Printed in Great Britain

2000 ton destroyer design of World War II. Such a ship would probably have had 40000 or 50000 shaft horse power installed and be capable of about 35 knots in calm water. However, experience showed that these ships were over powered and that this speed could rarely, if ever, be attained except in flat calm conditions. In severe weather the captain would be forced to limit power and speed to alleviate excessive ship motions, slamming, deck wetness and propeller racing.

Early postwar designs recognized this and about 3000 tons with 30000 shaft horse power and 25–30 knots calm water speed became the norm; hand in hand with this change of emphasis came a greater recognition of the need to consider rough weather performance at an early stage in the design process, before the main hull dimensions and proportions were frozen.

The best of these postwar frigate designs was the Type 12 which was developed into the Leander class, widely renowned for its good seakeeping performance and its ability to sustain speed in rough weather. The Leander was designed using intuitive knowledge of the effects of hull form on seakeeping (see Brown 1983). The importance of fine waterlines at the bow and deep draught to minimize slamming and the need for a high freeboard to reduce the incidence of deck wetness were clearly recognized. This limited the volume available at the forward end of the hull so that the bridge and main armament were pushed aft, resulting in a more comfortable ride for the crew. Nevertheless, Leanders were known in the Royal Navy as ‘lively’ ships which were liable to give their occupants a fairly exciting, but nevertheless tolerable, ride in rough weather. This reputation undoubtedly arose from the fact that the commanding officers felt confident that they could push the hull to its limits in rough weather because of its good inherent seakeeping properties, accepting an increase in the motions experienced by the crew. Perhaps this was the secret of their success; the design was well balanced and combined good performance at many aspects of rough weather behaviour without excelling or failing at any one in particular. This ensured that the ship was not significantly limited by any single aspect of performance.

Broadly speaking, the ship designer is, or should be, concerned with quantifying the ability of his ship to achieve its mission(s) in the weather conditions likely to be experienced in its expected operating area. It will then be necessary to decide whether this performance is acceptable. If it is not acceptable, changes will have to be made in the ship design or the operational procedures used.

This paper outlines some of the relevant techniques which have been developed in recent years and highlights the continuing need for objective data on the maximum permissible levels of the rough weather responses of the ship.

2. Ship motion calculations

Methods of calculating ship motions in realistic wave systems have been described in detail elsewhere (for example by Lloyd 1989). However, a brief description of the standard procedure is warranted.

The calculation starts with the assumption that the ship can be treated as a ‘black box’ (see figure 1) with the waves as input and ship motions as output. The black box is described by a set of transfer functions.

The transfer functions may be determined with scale model tests in a towing tank or by calculation. The latter is, of course, the preferred method and considerable effort has been expended in recent decades towards developing theoretical methods of adequate accuracy. The most successful and widely used of these are collectively

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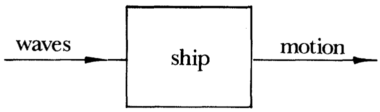
Figure 2

Figure 1



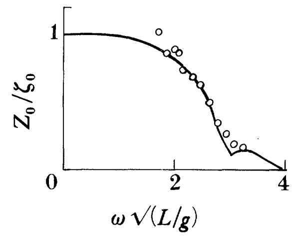


Figure 1. The black box ship.

Figure 2. Typical heave transfer function. Head waves, $Fn = 0.27$. ○, Experiment; ——, theory. (After Lloyd & Crossland 1990.)

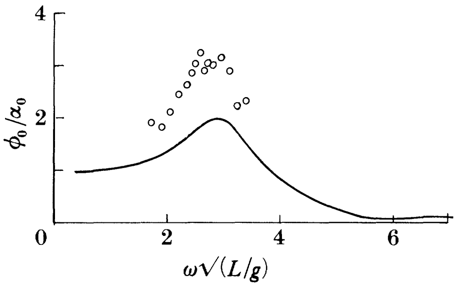


Figure 3. Typical roll transfer function. Stern quartering waves, $Fn = 0.27$. ○, Experiment; ——, theory. (After Lloyd & Crossland 1990.)

known as 'strip' theories because they represent the hull as a series of two-dimensional transverse slices or strips.

Comparisons between strip theory calculations of a heave transfer function and the results of experiments on a steered model frigate in head waves reported by Lloyd & Crossland (1990) are shown in figure 2. The ARE PAT-86 suite of seakeeping computer programs described by Andrew *et al.* (1984) was used for the theoretical calculations. The comparison is good and it is generally accepted that strip theory calculations of heave and pitch for conventional monohulls at conventional speeds are of adequate accuracy for everyday engineering purposes.

Figure 3 shows similar comparisons for roll in stern quartering waves. Here the discrepancies are unacceptable and it is clear that current versions of strip theory are not sufficiently reliable for predicting lateral plane motions. Further work is evidently required in this area.

For ship design purposes the wave energy spectrum is usually assumed to be given by the Bretschneider formula (for open ocean conditions) or the JONSWAP formula (for limited fetch coastal waters). Details are given by Lloyd (1989). Suffice it to say here that both spectra are defined by simple formulae in which the significant wave height and the modal period are parameters.

Information on likely significant wave heights and modal periods in specified sea areas and seasons can be obtained from the various wave atlases which have been published. Figure 4 shows, as an example, the annual percentage occurrence of various combinations of significant wave height and modal period for the northernmost part of the North Atlantic in winter.

St Denis & Pierson (1953) showed that the principles of superposition can be

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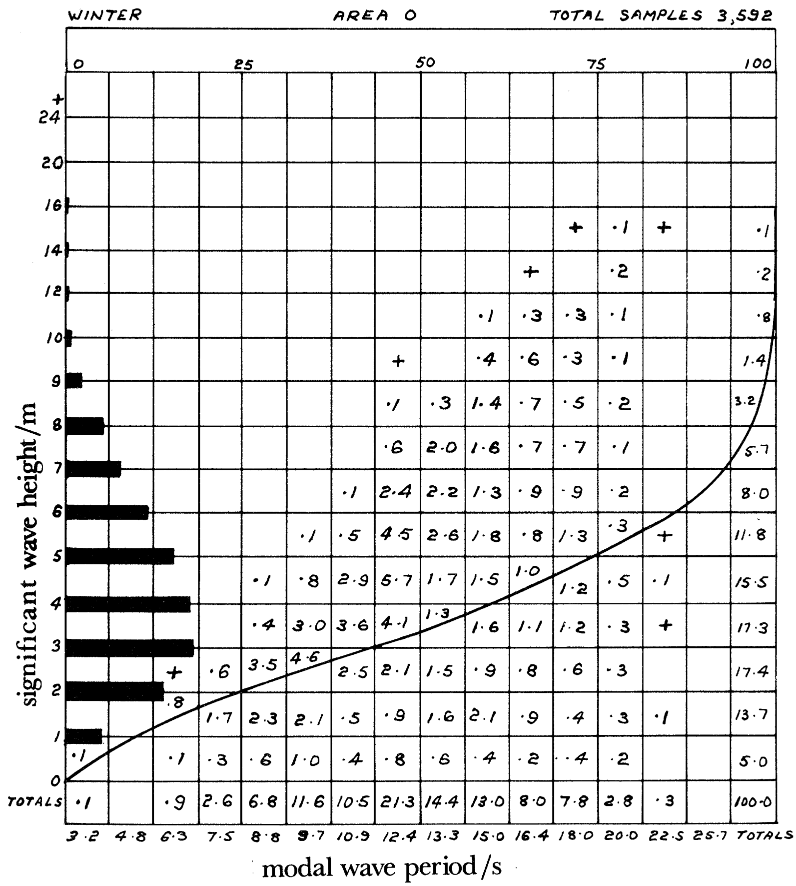

Figure 4. Wave statistics for northern North Atlantic. (After Bales *et al.* 1981.)

applied to the linear black box of figure 1 to determine the energy spectra of the motions in realistic irregular waves.

3. Criteria

Having calculated the motions his ship is likely to experience, the designer needs to establish whether those motions will be acceptable in practice.

At first sight it might appear that the goal should be to minimize all motions by suitable design. However, a certain level of ship motion is always acceptable and a better approach is to determine the motion levels which are tolerable and use these as design targets for some specified weather environment. This subject has been fraught with confused and muddled thinking in the past it is as well to lay down a set of 'rules' for determining ship response criteria.

3.1. *Mission*

The first requirement is to define the mission or task of the ship. Of course, ships have many different missions and it will be necessary to choose the ones of most immediate concern. For present purposes let us consider the task of launching, retrieving and maintaining a helicopter.

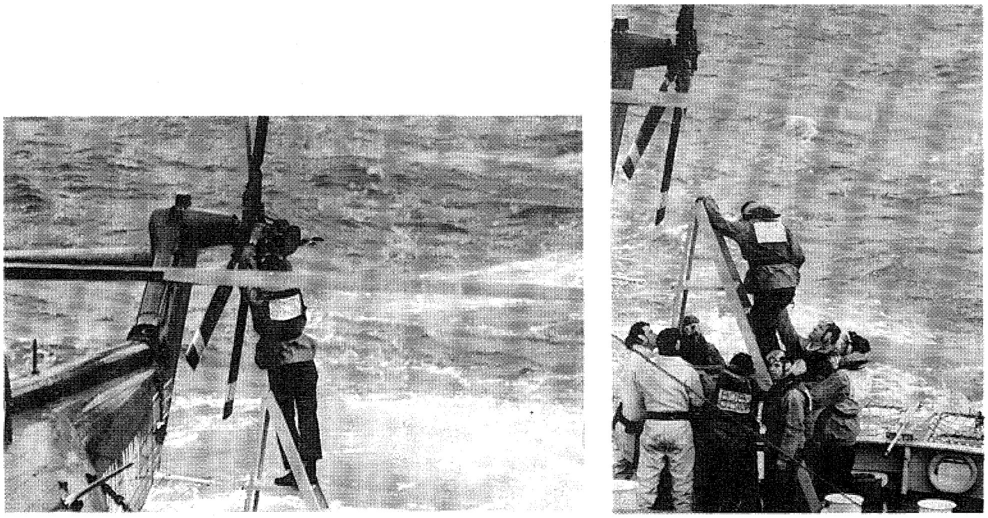

Figure 5. Removing tail rotor gust lock from a naval helicopter at sea.

3.2. *Task analysis*

The task of interest must be analysed in detail to determine the motions (or other rough weather phenomena such as slamming and deck wetness) which are likely to be of concern to those involved. Why can the task not be completed satisfactorily in rough weather? What aspects of the ship behaviour are significant in preventing timely completion of the task?

Great care should be taken at this stage to determine objective reasons for the rough weather degradation in performance. Figure 5 shows one of the tasks which may be required of the crew before the helicopter takes off. It is necessary to remove the tail rotor gust lock fitted to prevent damage to the tail rotor in gusting wind conditions.

Clearly there is a danger of the man falling from the top of the ladder if ship motions are excessive and wind loads must also be a problem. Judging by the number of his colleagues clustered around the bottom of the ladder this is clearly recognized by all involved. In addition the motions of the ship may make it more difficult to fit the lock with the required degree of precision. It would be pertinent to ask what ship motions are likely to cause the man to fall? What ship motions will make him to take longer to remove the lock?

A certain degree of precision must be brought to bear here. A loose answer to the first question might be that he will fall when the ship rolls heavily. Observations of many such exercises might show, for example, that the man falls when the roll amplitude exceeds, say, 5° in a particular ship; but common sense and experience show that people on dry land are able to maintain their balance without difficulty on a slope of 5°. It follows that it is not the roll angle as such which is of particular concern to the crew. Some simple modelling is useful here and it is possible to show that the man is likely to fall when his weight vector moves outside certain limits. So a more relevant assessment of the motion environment would take account of the local vertical and lateral accelerations at the man's position rather than just the roll amplitude (although, of course, the roll motion will contribute to the local accelerations).

The general problem of assessing human response to ship motions is particularly difficult because the actual tolerable levels of ship motion are dependent on factors such as mood, anxiety, age, fatigue, seasickness, etc. Moreover, the crew (and passengers) may have the freedom and ability to take remedial action such as altering their stance, lying down or moving to a more comfortable part of the ship. Tasks associated solely with inanimate objects (without human participation) may be easier to analyse objectively.

3.3. *Criteria determination*

Having established the rough weather responses which are of concern to the task of interest, the next step is to establish maximum permissible levels or criteria. The assumption is made that the performance degrades as a function of the increasing response level as shown in figure 6. Here the performance at the specified task is assumed to be at calm water levels (say 100%) for low motion levels: as the motion increases the performance can be expected to degrade in some way and the simplest assumption is that the performance is suddenly reduced to zero as the criterion level is exceeded. In practice a more gradual degradation of performance is probably the norm and certainly desirable. However, experience has shown that the assumptions made here have little effect on calculations of overall operational effectiveness.

A suitable measure of performance might be taken as the time required to complete the task in calm weather compared with the time required in rough conditions: performance is T_{calm}/T_{rough}.

In principle the best way of determining criteria is to observe the performance of typical operators in realistic conditions and note the circumstances when their performance begins to degrade. A prerequisite to this is, of course, the identification of the motions which are important to the task (as described above) and the provision of suitable instrumentation to measure them. In principle dedicated sea trials are the best way of obtaining such data. However, such trials are fraught with practical difficulties: there is no control over the primary variable (the waves); the performance of the operator will be influenced by many factors other than the motions and extensive and carefully controlled trials will be necessary to eliminate these extraneous effects; the results will be specific to the equipment involved.

For these reasons few trials have been attempted. A related alternative is to use a ship motion simulator as used in O'Hanlan & McCauley's experiments on seasickness (1974). Typically a cabin or platform is mounted on suitable machinery capable of oscillations in a number of degrees of freedom. The machinery may be driven by sinusoidal motion signals or irregular signals derived from measurements on ships at sea.

Here, at least, the motions can be controlled but simulators always lack a certain degree of realism (limited motion capability, no wind or spray, the wrong noises and smells, difficulty of acclimatizing the subjects properly, etc.) and this may have important effects on the results. Moreover the limited size precludes many studies involving sizeable equipment or substantial movement by the subjects. To date there have been no published motion simulator studies relating crew task performance to motions.

One technique which has yielded useful results in the naval context is to canvass the opinions of seagoing personnel using questionnaires. Sailors are asked to estimate the maximum sea conditions in which a certain operation is possible. The question is posed in a set scenario specifying the ship speed and heading. This allows the

Figure 6

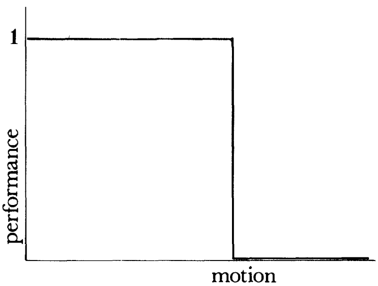

Figure 7

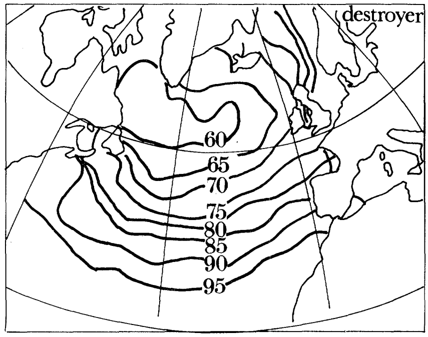

Figure 6. Assumed relationship between performance and motion.

Figure 7. Percentage operability contours for a destroyer in the North Atlantic in winter. (After McCreight & Stahl 1985.)

Table 1. *Limiting criteria for vertical acceleration after Karppinen (1987)*

vertical acc. r.m.s.	description
0.275 g	simple light work; most of the attention must be devoted to keeping balance; tolerable only for short periods on high speed craft
0.2 g	light manual work by people adapted to ship motions; not tolerable for long periods; quickly causes fatigue
0.15 g	heavy manual work by people adapted to ship motions: for instance on fishing vessels and supply ships
0.1 g	intellectual work by people reasonably well adapted to ship motions (i.e. scientific personnel on ocean research vessels); cognitive/manual work of more demanding nature; long-term tolerable for the crew; the International Standard ISO 2631/3 (1985) for half an hour exposure period for people unused to ship motions
0.05 g	passengers on a ferry; the International Standard for two hours exposure for people unused to ship motions; causes symptoms of motion sickness (vomiting) in *ca.* 10% of unacclimatized adults
0.02 g	passengers on a cruise liner; older people; close to the lower threshold below which vomiting is unlikely

motions in the estimated limiting conditions to be calculated at leisure using strip theory computer programs as described above. These motions can then be taken as estimates of the motion criteria for that particular class of ship engaged in the particular specified task.

Karppinen (1987) has proposed a useful table of limiting vertical accelerations for various activities and this is reproduced in table 1.

4. Performance assessment

Having established the limiting criteria the next step in a seakeeping assessment is to estimate the performance of the ship in the weather conditions it is likely to encounter during its lifetime at sea. Suitable techniques were described by Andrew

Table 2. *Hull form requirements for good seakeeping after Lloyd (1988)*

	stable platform	high mobility	consensus
draught/length	low	high	?
beam/length	high	low	?
transom draught/draught	unimportant	unimportant	unimportant
transom beam/beam	high	unimportant	high
forward waterplane area coefficient	high	high	high
midships area coefficient	unimportant	high	high
block coefficient	unimportant	low	low

et al. (1984). Basically the technique requires the responses to be calculated for every speed and heading to the waves in all the wave conditions which occur in the sea area and season of interest (see, for example, figure 4). For a typical assessment this requires several thousand calculations of the motion responses and each result is compared with the corresponding criterion estimated earlier.

If any of the responses exceeds its corresponding criterion the task cannot be achieved in the specified conditions. Using the probabilities of occurrence of the wave conditions as weighting factors it is then possible to calculate the proportion of time the task can be accomplished in the specified sea area. This can be used as a figure of merit for the ship design. Figure 7 shows the results of such a calculation for a destroyer operating in the North Atlantic in winter.

5. Optimization

If the performance estimated in the ship's working environment is deemed inadequate, the design must be altered to improve matters. Guidance on suitable changes may be found in published papers, notably by Bales (1980), Schmitke & Murdey (1980) and Lloyd (1988).

Lloyd (1988) made a distinction between the design requirements for a stable platform (i.e. a ship with small absolute accelerations giving superior crew and passenger comfort) and a high mobility design (one with infrequent slamming and deck wetness and no regard for crew and passenger comfort). Table 2 shows the desirable features for a good hull form with a specified length. It can be seen that the requirements are not generally incompatible: but the high mobility design requires a narrow beam and a deep draught whereas opposite proportions are required for the stable platform. It is for the designer to choose a suitable compromise between these conflicting requirements. High waterplane and midships area coefficients are generally desirable and a wide transom is also beneficial.

6. Conclusions

This paper has outlined the techniques available to ship designers for estimating the performance of a new design ship in rough weather. Strip theory calculations of motions in the vertical plane are generally agreed to be of adequate accuracy but further work is required before predictions of lateral plane motions can be given the same seal of approval.

Some progress has been made in developing a strategy for determining maximum permissible levels of the rough weather responses of the ship. It has been shown that these must depend on the mission or task of the ship and that there can be no set of universally applicable criteria.

Once criteria are established they can be used in an overall assessment of the merits or the design. The relevant rough weather responses are calculated in all likely conditions of wind, waves, speed and heading and the results are used to determine the proportion of time that the criteria are not exceeded in a given sea area and season. This can be taken as a figure of merit for the design on the specified mission.

If the figure of merit is deemed to be unacceptable it will be necessary to modify the design and repeat the process. Limited guidance on suitable design changes has been given, but further work is required in this area.

Application of the techniques described in this paper will allow seakeeping to take its rightful place in the present day design process. This should allow designers to avoid some of the mistakes of the past and ensure that the rough weather performance of new designs is even better than that of the Leander.

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Discussion

R. Hosoda (*University of Osaka Prefecture, Japan*). I basically agree with Dr Lloyd's opinion for the research attitude of seakeeping performance. The seakeeping performance of a ship is to be evaluated focusing whether the assigned mission can be achieved or not. (We named it as *mission effectiveness* (Hosoda & Kunitake 1985).) His opinion for the seakeeping research is to determine the maximum permissible levels of ship responses. However, I think that the most important and most difficult item of seakeeping performance study is the estimation and evaluation of human performance degradation that necessarily occurs explicitly and/or implicitly. To achieve this final goal, I think researchers in ship performance and ship dynamics have to study the mechanism of motion induced human performance degradation from the view point of ergonomics.

Another aim of seakeeping performance to be evaluated is performance guarantee of ships in a seaway. The speed guarantee has to be done at the early stage of performance design. For this purpose, the estimation of seakeeping performance, especially estimation of added resistance and propulsive efficiency in winds and waves, is important and may change the initial design procedure. Can a ship's performance, and ship speed be guaranteed five years after delivery for instance.

A. R. J. M. Lloyd. The original (over long) version of my paper included a section on the effect of ship motions on human performance and seasickness. Professor Hosoda's comments are therefore very welcome and I endorse his suggestion that further work is required in this field. Some work has been done relating the incidence of seasickness to the severity and type of motion but most of the emphasis has been on testing anti seasickness drugs. Little or no work relating human performance to motions has been published. However, we are involved in a cooperative project (with establishments in Canada and the United States) which will involve the testing of human subjects in a ship motion simulator. The intention is to measure performance of volunteer Navy personnel at various simple standard tasks (both physical and mental) while the motion simulator is driven using recordings taken from ships at sea.

This approach is regarded as preferable to attempting to measure performance at sea with all the problems of lack of control over experiment conditions. However, simulators can never reproduce the at-sea environment exactly and there is always some lack of realism.

Added resistance and propulsive efficiency in waves are not usually considered very important factors in the design of high speed naval combatants since voluntary reduction of speed by the captain to avoid slamming, deck wetness and excessive motions is the most important cause of speed reduction in rough weather. I therefore do not feel well qualified to answer Professor Hosoda's second question, although I understand that the accurate prediction of added resistance remains difficult for blunt bow ships.

The merit of the operability contours of figure 7 is the ease with which they may be understood and their consequent immediate impact. An admiral ordering a new destroyer is likely to be very impressed with the prediction that his ship will only be able to operate for 60% of the time in parts of the North Atlantic in winter. It must, however, be remembered that these contours depend on the criteria selected and it would be easy to paint an unduly pessimistic picture by selecting low values which were difficult to achieve. For the record McCreight & Stahl used the following criteria (motions given as significant single amplitudes): 8° roll; 3° pitch; 0.4 g vertical acceleration at the bridge; 20 slams per hour; 30 deck wettings per hour.

D. W. Robinson (*Lloyd's Register, London, U.K.*). Although it is normal to use a linear strip theory to compute ship motions, recent measurements in severe seas carried out by Lloyd's Register on a large containership showed a distinct difference of magnitude between bow up and bow down motions. Has this been witnessed in model experiments and is it important for estimating the absolute relative motion at any point on the ship?

A. R. J. M. Lloyd. We have experienced asymmetric relative motions and examples are given in Lloyd *et al.* (1986). These can be partly attributed to a different local running waterline ('bow wave') and the asymmetry can be removed, to some extent by measuring the motions from this datum. However, this may not be the whole story and there is some evidence in the paper to show that the probability of exceeding a given bow down motion level may be greater than the corresponding probability for bow up motions.

K. Nicholson (*Portsdown, U.K.*). As a member of the Surface Weapons section of the Admiralty Research Establishment, I was interested to see the operability contours shown by Dr Lloyd for a frigate in the northern North Atlantic. He pointed out that these were derived from a number of ship motion calculations, at a range of headings, and the determination of the exceedance of a set of criteria. This process obviously depends on the calculation of not only vertical plane motions but also those in the lateral plane, including roll. He also pointed out that the roll predictions did not seem to show good agreement with model results. Therefore, what is being done to improve these predictions of lateral plane motions so that we can have greater confidence in the resulting contours? Even as comparitors, the implications of the contour results could have a significant impact upon whether the customer decides to acquire a surface ship for use in those areas or choose to perform his task in some other way.

A. R. J. M. Lloyd. Dr Nicholson rightly points out that the operability contours are also dependent on the accurate prediction of the motions and that these are in doubt for the lateral plane. Since the evidence of figure 3 suggests that roll motion is underestimated this suggests that the operability contours may be even more pessimistic than suggested here. We are currently involved in a programme of work aimed at determining the reasons for these discrepancies. We are looking at wave excitation forces and moments as well as roll damping and roll response on two-dimensional models of typical hull section shapes. We are also examining the wave excitation on a complete model ship hull at zero forward speed. I believe that at least part of the discrepancy may be due to the surging motion experienced in these quartering wave conditions. This is ignored in the five-degree-of-freedom mathematical model and will result in the position of the ship on the wave and the consequent phasing of the roll moment excitation being incorrectly assessed. This could explain the fact that the discrepancies are only significant in quartering seas where surge amplitudes are large.

G. Victory (*Surrey, U.K.*). Dr Lloyd rightly points out that the ship motions obtained from regular wave transfer functions require to be amended to obtain statistics for ship motions in irregular waves. I doubt whether this is possible, for in 12 years at sea I have yet to see a wave motion which was regular, or in most instances even remotely predictable! Dr Lloyd rather confirms this and admits there are no universally applicable criterion while stressing that long-term onboard records of ship motion under all weather conditions are needed to decide whether specific duties can be expected to be performed within the weather envelope.

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This combination of taking theory as far as it will go but relying on actual performance data to confirm or confound the theory is to be applauded, but is not always followed. I can only ask Dr Lloyd if he will admit that there are conditions which his records have not experienced, and ask what 'factor of ignorance' he would apply if he were to be asked to specify the worst conditions and ship motions which might be experienced at some time in a ship's life.

A. R. J. M. Lloyd. I fear that I may not have made myself clear to Mr Victory. The standard technique for predicting motions in realistic irregular waves involves the following steps: (1) measure or predict the motion transfer function in regular waves; (2) filter the irregular wave energy spectrum with the transfer function to obtain the motion energy spectrum; (3) integrate the motion energy spectrum to obtain the motion variance; (4) obtain the r.m.s. motion in the irregular waves from the square root of the variance.

A time history of the motion in the irregular waves can be obtained by summing a number of sine waves whose amplitudes are determined from the motion spectrum. This will have the appearance of a truly random motion. There is no suggestion that the motions at sea are in any way regular or predictable from second to second. Rather the statistical nature of the motions is fully recognised and we generally deal in probabilities and r.m.s. values.

Criteria for acceptable motions must also be written in statistical terms. It may be possible to show that a certain operation cannot be accomplished if the roll angle exceeds, say, 10° (a deterministic criterion) but we need to specify how frequently this may occur before the performance is degraded to an unacceptable level. Thus a suitable criterion might be written in the form: 'the roll motion must not exceed 10° more than once a minute' or 'the roll motion must not exceed 10° for more than 10% of the time'.

My comment that there are no universally applicable seakeeping criteria was intended to emphasize that the criteria depend on the task: a motion which is acceptable for one activity is not necessarily acceptable (or even relevant) for another.

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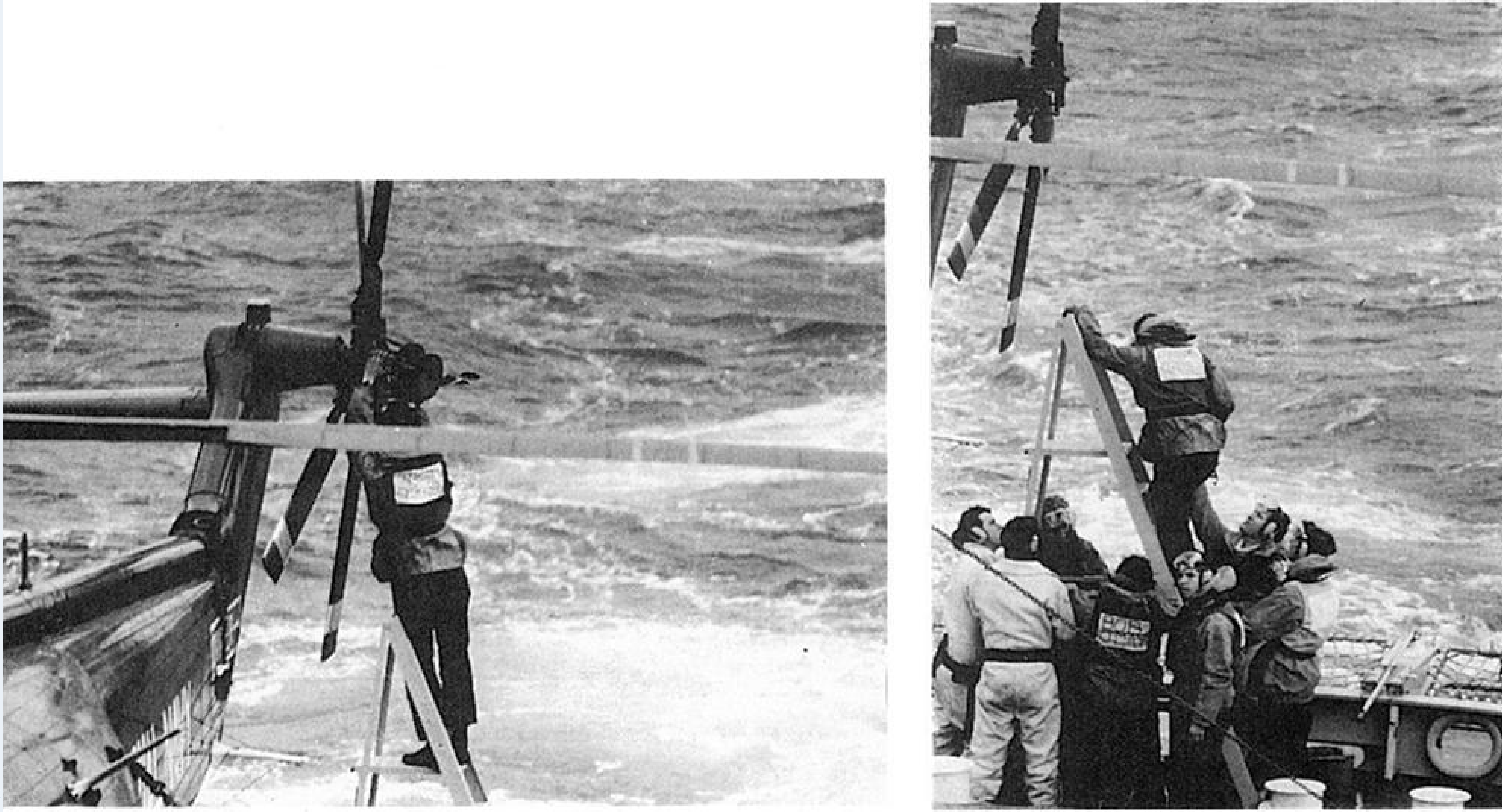

Figure 5. Removing tail rotor gust lock from a naval helicopter at sea.

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