1 Ship response

Fanned by a favouring gale,
You'll sail
Over life's treacherous sea
With me,
And as for bad weather,
We'll brave it together...
Ruddigore

1.1 The effects of waves on ships
When a ship proceeds through waves it executes motions that it does not perform when it moves through flat calm water. These parasitic motions raise a number of serious questions and it will be helpful to discuss the motions and their effects in general terms at the outset.

1.1.1 Increased resistance
A ship suffers increased resistance in rough sea. That is to say, for a given propulsive thrust its speed is lower, and the higher the waves the greater is this involuntary loss of speed. This behaviour is represented in a rough and ready way in fig. 1.1, though it is really a matter for conjecture what happens to ship resistance when the significant wave height is great because effects other than mere increase of resistance begin to intervene. The loss of speed is then a matter of choice, being ordered by the ship's master so as to lessen other ill effects of a more pressing nature.

Fig. 1.1. A sketch illustrating the effects of waves on ship performance. To the left of the broken line, the curve represents involuntary loss of speed due to increased resistance. To the right, the loss of speed is voluntary, depending largely on the judgement of the ship's master.
Ship response

Resistance in waves is not a well-understood subject. Several attempts have been made to calculate it, and a number of theories exist by which estimates can be made.

1.1.2 Deck wetting
If a ship’s master attempts to drive his vessel too hard in heavy seas, he may cause it to suffer damage by ‘digging in’. The bow may dip beneath the surface so that water breaks over the upper works. The ship is said to be ‘shipping green water’ or to suffer ‘deck wetness’. Numerous films have been made of warships shipping water in this way since, for them, the need to maintain speed in heavy seas is a matter of concern and therefore of research. These films make it very plain that deck wetting can be extraordinarily severe. (It is not unknown for the forward end of the flight deck to dip beneath the waves when a large aircraft carrier is driven hard in heavy seas.) When severe deck wetting occurs, no one could survive on the ship’s forecastle and serious damage may be done to the deck fittings. Some idea of the ferocity of the conditions can perhaps be gained from fig. 1.2, which shows a frigate with its bow dug well into the sea.

Fig. 1.2. A frigate on trials experiencing severe deck wetting. (Photograph by courtesy of the Royal Navy.)
1.1.3 Slamming

Fig. 1.3 shows a frigate with its forefoot lifted clear of the water surface. Provided the relative velocity of the ship's bottom and the sea surface is large enough, the vessel will 'slam' when its forefoot re-enters the water. That is to say, an impulsive loading will be applied which will make the ship shudder and may well cause damage. The bottom plating of a steel ship may fatigue, local damage may be done due to overstressing and equipment (particularly sonar domes) may suffer as a result of the shock loading. Some ships are left vibrating significantly for comparatively long periods of time after one of these impacts. Fig. 1.4 shows a strain gauge signal taken from the hull plating of a ship following a severe slam.

The possibility of frequently repeated slamming in a heavy sea is a very real one and a ship's master could well jeopardise his ship by allowing it to happen since the effects of slams are in some degree additive. For this reason, too, it is necessary to slow down when conditions require it.

There are two related phenomena, neither of which is well documented yet both of which are worthy of mention. First, when a ship's

Fig. 1.3. A frigate with its forefoot lifted out of the water. When the bows re-enter, the impact of the sea may cause severe stressing of the hull. (Photograph by courtesy of the Royal Navy.)
Ship response

brows have a marked flare (as with some high-speed vessels or the forward end of the flight deck of an aircraft carrier), rapid immersion can severely strain the vessel. Secondly, it is known that some ships may suffer slamming at the stern in a following sea. Although this behaviour is not as common or as violent as slamming at the forefoot, it is still a serious matter since a ship is most vulnerable at its stern as that is where the propeller and rudder are located.

1.1.4 Vertical acceleration

It is not known with any precision what causes sea-sickness. Many factors play a part (including lack of fresh air). The same can be said of the other ways in which human performance may become impaired in heavy seas. Perhaps the best practical guide is vertical acceleration; at all events this is commonly used in deciding which motions in a seaway are acceptable if severe loss of human performance is to be avoided. A ship’s master may very well have to reduce speed in heavy seas to prevent conditions from becoming virtually intolerable for the crew or for a fragile (possibly live) cargo. In conditions like those of fig. 1.5, however, severe loss of human performance is probably quite unavoidable in a small vessel like the one shown.

1.1.5 Stressing

A ship is a more or less elastic body and, quite apart from slamming, waves cause it to distort. In other words, time-dependent strains are set up in the hull which are superimposed on those that are present in still water. Fig. 1.6 shows the stern of a tanker which split because stresses in the plating were excessive. (Tankers have been lost as a result of explosion in a tank, but there was no suggestion from the survivors of this ship that an explosion occurred.) This book is very much concerned with this aspect of wave response.

Leaving aside slamming for the present, it would be misleading to imply that a ship's master reduces speed in heavy seas in order to limit stresses in the hull. In fact he has no accurate means of judging what the stresses and strains are, let alone how serious they may be. If, then, stresses are to be limited by reducing speed, the naval architect (in the capacity of ship designer or ship surveyor) should place restrictions on operating conditions, or else furnish the master with some sort of monitoring device.

Fig. 1.4. A strain gauge signal taken from the hull of a merchant ship showing response to a slam. The high-frequency oscillations have a frequency of about 0.9 Hz, while the low-frequency component is of approximately 0.1 Hz.
Fig. 1.5. The conditions in this ship as it weathers a severe gale must be difficult and normal working must be quite impossible. (Photograph by courtesy of the Royal Navy.)

Fig. 1.6. The stern of the 153 m tanker *Gem* which split in early March 1962 off Virginia. Survivors reported that the ship broke in two ‘with a cracking sound’.
1.2 **Response to wave excitation**

The various phenomena that we have mentioned provide the ship designer with some difficult problems. Briefly they reduce to that of designing a ship that its responses to waves are as small as possible. The responses may be bodily motions of the hull as a whole (as if it were rigid) or they may be distortions of some form or other. In other words he must be able to estimate responses for different wave- and operating conditions by investigating the way in which suitable parameters vary.

1.2.1 **Motion responses and distortion responses**

In the past it has been the custom to distinguish sharply between the ‘motion responses’ and the ‘distortion responses’ of a ship. Motion responses of a rigid ship have been dealt with in the theory of ‘seakeeping’ on which there is a large literature. Hull stressing on the other hand has been investigated in a semi-empirical fashion, stresses being held to be of two sorts – those that would be set up in a rigid ship, and those which must be added, if necessary, by way of a correction for something called ‘springing’. An approach of that nature must eventually be discarded (as its predecessors were) and refuge will presumably be taken in more basic principles of the dynamics of a deformable body.

It is a return to first principles that we shall attempt to accomplish in this book, and our approach will be that of ‘linear modal analysis’. This approach allows us to do two things:

(a) strength analysis can be rationalised, and
(b) seakeeping theory can be reconciled and combined with the strength analysis.

Note particularly that this does not mean either that we can produce, ready made, a working set of design rules which will immediately supplant those that are already in existence, or that all existing theory is valueless. A tremendous amount of practical knowledge is reflected in the present rules and the need now is to sift that knowledge carefully with a view to making it more reliable and more useful in ship design. That will take time.

1.2.2 **Selection of coordinates**

The structural dynamicist may be forgiven if he assumes that the choice of coordinates for investigation of ship response presents no problems. The computer will permit him to select hundreds of coordinates if he so wishes. Unfortunately things are not that easy. At some stage it becomes necessary to estimate hydrodynamic actions and that is virtually impossible to do with precision and economy without *convenient* measures of structural motion. Unless the naval architect is prepared to invest an unrealistic amount of time and effort in some
Fig. 1.7. Outlines of some typical hulls. The hulls are drawn with the same length to differing scales so as to show the differing degrees of realism involved when regarding a ship's hull as a 'thin beam'.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Weight loaded MN (tonne-f)</th>
<th>Approx. dimensions in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1871 (190 800)</td>
<td>LOA 326, Beam moulded 47.2, Depth moulded 23.7, Type Tanker</td>
</tr>
<tr>
<td>2</td>
<td>382 (38 940)</td>
<td>LOA 201, Beam moulded 25.9, Depth moulded 14.4, Type Bulk cargo carrier Frigate</td>
</tr>
<tr>
<td>3</td>
<td>41 (4 184)</td>
<td>LOA 130, Beam moulded 13.6, Depth moulded 10.3, Type Frigate</td>
</tr>
<tr>
<td>4</td>
<td>640 (65 200)</td>
<td>LOA 224, Beam moulded 31.7, Depth moulded 15.7, Type Tanker</td>
</tr>
<tr>
<td>5</td>
<td>176 (18 000)</td>
<td>LOA 156, Beam moulded 19.5, Depth moulded 12.3, Type Cargo ship</td>
</tr>
<tr>
<td>6</td>
<td>5.43 (554)</td>
<td>LOA 55.1, Beam moulded 9.5, Depth moulded 5.3, Type Pilot vessel</td>
</tr>
</tbody>
</table>
form of finite element analysis, he is almost forced to think in terms of a ‘beamlike’ ship. How reasonable this is, is very much a matter for speculation.

Fig. 1.7 shows the outlines of a few types of vessels and it has to be admitted that some are decidedly more beamlike than others; that is to say some are far more slender than others. Paradoxically perhaps, the large tanker of cathedral-like proportions (fig. 1.8) is in fact the thinnest beam. Fortunately it is possible to make some allowance for lack of thinness of the ‘hull girder’ if necessary.

The coordinates that we shall use are the principal coordinates of the dry hull. These will admit motions of the beam as well as distortions. Since we have agreed that the hull is beamlike we can employ the words ‘bending’ and ‘twisting’ without ambiguity. Symmetric distortion occurs in bending modes, while antisymmetric distortion occurs in modes that involve both bending and twisting (which may or may not be coupled). The principal coordinates are measures of deflection in the various principal modes. But there is a drawback – it is

Fig. 1.8. As the men standing on the fore deck of this large tanker make plain, the vessel is of truly gigantic size. Yet such a ship is very well represented for the purpose of dynamical analysis as a thin beam.
not possible to find an unsupported dry hull, let alone to observe its behaviour.

Other sorts of coordinates can be used to specify ship response, but the only serious alternative to those we have mentioned seems to be the set of principal coordinates of the wet hull. At least the behaviour of a wet hull can be observed. Unfortunately these latter coordinates suffer from serious disadvantages; thus

(a) the deflection corresponding to unit value of any particular coordinate is dependent on the hydrodynamic theory that is chosen to represent fluid actions if modes are to be defined for the wet hull;

(b) the precise meaning to be assigned to the ‘principal coordinates of the wet hull’ is by no means obvious, any more than the properties of the relevant modes are.

1.2.3 Estimation of response to waves

Having seen why one should wish to estimate ship responses and how they might be specified, we have now to think about how those responses might be obtained. Since that is the object of this book we shall briefly outline the approach we shall use.

The dynamical ‘system’ with which we are concerned is a dry hull. In other words all fluid actions – be they due to hull motion or to waves – are to be thought of as ‘applied’. Our first task, then, is to examine the hull and to derive appropriate equations of motion.

We shall discover that the fluid actions can be regarded as being of two distinct sorts. Some fluid forces applied to the hull are those which would be due to the actual motion of the hull if that motion were performed in flat calm sea. The second type of fluid actions are those that would be applied by the waves to the hull if the hull had no motion. The wave actions are found, ultimately, from the observations made by physical oceanographers. We shall therefore deal with the business of putting the entries in a wave atlas to use in ship design. With this task completed we shall have assembled our ‘input’ data.

The ‘output’ is a motion, a bending moment, a shearing force, a stress, or some other quantity whose variation is of interest, and in a sense its derivation completes the task before us. Unfortunately there remains the difficult task of assessing the results of these calculations. We must try to assess the motions and stresses that are set up in a hull.

1.2.4 The assessment of responses

The assessment of ship response is not at all an easy subject. The analyst can try to estimate the incidence of deck wetting or some other form of output for given conditions. But the absolute and relative degrees of importance to be assigned to these results really lies in the province of the ship designer.
The design of a ship is an enormous undertaking and the profit to be derived from piling more and more responsibilities on the designer is perhaps open to question. But, particularly with large flexible ships, he is providing himself with some hitherto unexpected problems. We can all agree that the size of the galley, the layout of the bridge, and so forth, are important, so ‘architecture’ matters a great deal. But where the integrity and performance of the vessel is concerned, the technology is (or should be) that of hydroelasticity, and ship designs have to be judged in the light of it.

To take an example, over the last few years it has become apparent that hull fatigue can be a serious matter. Does it follow that, because the vast majority of ships do not suffer serious damage from this source they are grossly ‘over-designed’? This is not a question that can be answered with much confidence – rather little is known about the fatigue properties of steel in sea water – so how can hull distortions be assessed even if they can be estimated? The fact that this is an area of very considerable difficulty, so that recourse has to be had to empirical rules, is a very poor reason for failing to try to get at the truth. We must learn to estimate the output responses of various sorts and to assess their importance.

Even at sea in an actual vessel, the assessment of response to waves is in some respects exceedingly difficult. When a ship is in heavy seas, the master has to weigh up conflicting requirements. His first concern is for safety, but safety can only be bought at a price and he must decide to what extent he must exercise caution. He will not want to miss tides at his destination, he may have a tight sailing schedule, he may in times of war have other very pressing reasons for wishing to maintain speed. Different captains will inevitably reach different decisions in the same circumstances, because they have different temperaments if for no other reason.

But things are not really as simple as this. The master’s decision to slow his ship down (to lessen slamming for instance) is based on his own observations. When he feels violent shuddering after a slam he is more likely to slacken speed than when he does not. If his bridge is located at an antinode in an appropriate mode he may be unduly cautious, but if it is at a node he may not slacken speed enough. Again the captain can under- or over-estimate the ill effects of waves on his crew for comparable reasons.

So one can go on. What, for instance, should be regarded as an acceptable incidence of deck wetting? Personal judgements play a vital role in ship operation and crucial decisions are reached with the wisdom born of experience. This is an area where we need much more information on the so-called ‘man–machine interface’.

1.3 Excitation by machinery
It seems largely to have been overlooked in the past that excitation of a