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

Some Comments on Present-Day Ship Dynamics [and Discussion]

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Some comments on present-day ship dynamics

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This introductory paper highlights some of the issues that motivate the international gathering of eminent engineers and scientists attending this Discussion Meeting on the dynamics of ships.

1. Early work in ship dynamics

If we accept that ship dynamics relates to the behaviour of hulls in which inertia forces play a significant part, then ship dynamics cannot be described as a new subject. On the contrary, it is both old and very large, judging by the literature. We are confronted by a well-rehearsed subject with its foundations resting on the pioneering studies of William Froude (1955) and his son Robert, who, more than a century ago, conducted the first scientifically designed towing tank experiments using scaled ship models travelling in calm water or in waves.

The literature is too large to review in detail though the works of Robb (1927), Saunders (1957), van Lammeren (1962), Korvin-Kroukovsky (1961) and Comstock (1967) provide valuable and extensive descriptions of the traditional subject material of naval architecture. The last two publications remain widely used today, even though these compendia of knowledge on ships dynamics appeared in the 1960s, both with the sponsorship of the Society of Naval Architects and Marine Engineers in the U.S.A.

The first, a lengthy monograph on *Seakeeping* by Korvin-Kroukovsky (1961), is concerned mostly with the motions of ships in rough sea. The writing of this book was no superficial effort. Its author cites no fewer than 479 references in the first chapter (on the seaway) alone, and sometimes quotes specific writers at length. In fact, the dynamics of a rigid ship is dealt with both very systematically and in quite awesome detail.

The second compendium edited by Comstock (1967) is *Principles of naval architecture* and it, too, sets out the state of existing knowledge in great detail, consisting of eleven chapters, each written by an acknowledged authority. Again the book can be relied upon as an accurate and detailed statement of the state of ship dynamics at the time of its appearance. (The principles of naval architecture seem to be almost synonymous with those of ships dynamics.)

With a background like that set out in these two massive books, the newcomer might be forgiven for thinking that ship dynamics is a subject that has long been 'solved'. Unfortunately, losses at sea have not become a thing of the past, as casualty returns make clear. It remains depressingly easy to find that well-found ships, properly surveyed and operated by competent crews, have foundered. For example, from articles published by M. Grey in Lloyd's List on 3 August and 8 August 1988 it is revealed that, for one reason or another, over 160 bulk carriers

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have been reported as total losses since September 1980, some of them modern ships and one is left wondering what is wrong. Furthermore, the question is one of some urgency because international economics depends upon the carriage of bulk cargoes in ships. In short, we have some serious questions to ask and to answer.

This awkward state of affairs has, of course, been very well known for many years. The whole field of ship science is kept very much under review by various organizations. The International Towing Tank Conference (ITTC) was founded in 1957 to coordinate work in the particular field of model testing. The Intergovernmental Maritime Organization (IMO) with its headquarters and meeting place in London, was established in 1959 under the aegis of the United Nations for the purpose of intergovernmental cooperation on shipping matters and safety. The International Ship and Offshore Structures Congress (ISCC) has monitored work on ship structures (and nowadays also offshore structures) since its inception in 1961. Both the ITTC and the ISSC remain very active, holding regular specialist meetings in centres around the world.

Again, trawler losses have not abated significantly in recent years. They were sufficiently high in the late 1960s for a Government Committee (The Holland Martin Committee of Inquiry into Trawler Safety which reported in May 1969) to sit on this problem in the U.K.; but judging from the number of losses since it met, little good emerged from that committee's work. Evidently the traditional idea of trying to estimate rolling motions in rough sea is simply not good enough as a prerequisite for preventing capsize, be the theory ever so clever and ever so nonlinear.

One thing is quite plain. Acquiring a complete knowledge of the whole of the literature in detail would be a huge undertaking. First mastering and then augmenting it by judicious improvements is not likely to be a particularly profitable approach. Something more radical is needed.

2. Trends in early research

Two aspects of ship dynamics are obvious, and it might perhaps be argued that they have largely dictated the course of history in this subject. They are (i) ship dynamics is a particularly difficult field of engineering research; (ii) economic pressures make ship design, and the dynamics upon which it is based, highly conservative.

The sheer complexity of ship dynamics led to the adoption of empirical assumptions of the most basic kind. Then the pressures of ship design, building and ownership ensured that the empirical assumptions were subjected to a process of 'improvement'; those assumptions became part of the accepted doctrine of naval architecture.

Ship stability first led to considerations of metacentric height. Then there came the *GZ* curve and the complications of cross curves of righting moments, and so forth, all to do with hydrostatics in flat calm water. After this came the dynamics of rolling, first in one degree of freedom and then in more than one. Gradually, the subject was elaborated and the history of this development can be gleaned from Korvin-Kroukovsky's book. The research work that this entailed was based upon an act of faith; if one could describe the process of rolling with sufficient accuracy, one should be able, eventually, to formulate criteria for the prevention of capsizing.

Similarly, the history of research in hull stressing started with the simple notion that a hull should be stressed as if it is balanced on 'heaps' of water at the bow and stern, and then on a 'heap' of water at the amidships section. This idea was introduced by Reed (1871) in a particularly elegant and readable paper. Here was a good practical way of approaching ship strength, a fact which is attested to by a colossal literature devoted to the improvement of Reed's original idea.

In the 1950s, there began to appear a new approach to ship strength. This was proposed by Korvin-Kroukovsky himself, by E. V. Lewis (1967), and by their co-workers. It was based on the notion that if the hull is assumed a rigid body, and the forces applied to it are determined, then a 'rational' approach to ship stressing can be formulated. it was at about this time when the two reference books referred to appeared. It has to be admitted that, as it was originally produced, the new method left a good deal to be desired on the side of structural dynamics; thus, understandably perhaps, little attempt was made to investigate the effects of coupling between degrees of freedom and orthogonality of modal responses. Even the nature of the modal properties were left a little vague.

By the 1960s, the computer was just beginning to play a significant part in ship dynamics. It was naturally used first to do, better and faster, the numerical work that was implicit in the existing literature. If this seems a somewhat sweeping generalization it is certainly borne out by Appendix A of Comstock's book. As in a good many other branches of engineering, the computer's ability to allow basic theory to be better exploited became more apparent rather later, in the 1970s.

In a very rough and ready way, then, this is more or less how ship dynamics appeared at the time when the two great reference books first appeared. It is perhaps fair to suggest that enormous effort had been put into development of ideas whose nature was essentially empirical and which had somewhat limited scope scientifically.

3. A perspective

It is tempting to start from the enormous body of theory that existed in the 1960s, to examine how ship dynamics has developed since then and to try to lay out a course to be steered in the future. Let us, rather, take a more fundamental point of view. A ship is an elastic structure which proceeds on the surface of a disturbed liquid. The problem is basically one of hydroelasticity in which physical oceanography is potentially important.

Of course, physical oceanography has progressed a great deal in the past twenty years. So, too, have structural dynamics and naval hydrodynamics. Modern random process theory, and statistical analysis more generally, have developed greatly. Yet again, the place of the computer is now seen to be quite central to ship dynamics and the day is long past when it was used as a sort of super slide rule. In short, we can begin to look at the hydroelasticity of ships in the terms of much more mature branches of science and technology.

An elastic ship moves bodily and also distorts. The bodily motions are those of surge, sway, heave, roll, pitch and yaw, and they are performed as if the ship does not distort. In addition, the ship may distort in an infinite number of ways. The hull responds to excitation by waves, by propellers, by the rudder, by stabilizers and by machinery within the hull. The subject of ship dynamics is really the study of these responses to given inputs.

It is necessary to assign coordinates to deflections at the various degrees of freedom and one particular set of generalized coordinates has at least the advantage of being unambiguous and easily comprehended. These are the principal coordinates of the dry hull. One may identify (*a*) in symmetric responses; heave, pitch, and vertical bending, all with respect to equilibrium axes, and (*b*) in antisymmetric responses; roll, sway and yaw, horizontal bending and twisting, again all with respect to equilibrium axes. For this approach, then, one needs six principal coordinates for rigid body motions and then as many generalized coordinates for symmetric and for antisymmetric motions as is thought necessary.

The adjective 'symmetric' is here used in the port/starboard sense. This may not imply, of course, that the structure itself is symmetric port and starboard, as is certainly the case with aircraft carriers and with side loading roll-on–roll-off vessels, for example.

Reference is being made to the use of *equilibrium* axes. These are frames of reference which travel with the vessel at its reference speed through the water and the parasitic motions referred to are performed relative to that frame. While this formulation has advantages in rectilinear motion, it brings considerable difficulties when one is concerned with turns and manoeuvring in general. Here it may be preferable to use *body* axes when distortion is not thought to be significant. Then the relative coordinates would relate to (*a*) for symmetric motion; surge velocity, heave velocity and pitch angular velocity, and (*b*) for antisymmetric motion; roll angular velocity, sway velocity and yaw angular velocity.

We have identified two possible ways of assigning generalized coordinates; one for equilibrium axes and one for body axes. Generally speaking, it is convenient to identify the former with distortion responses, by wave excitation and by excitation from machinery; the latter by contrast are most useful in problems of seakeeping and manoeuvring. It is not unreasonable to suggest that the equilibrium axes are of most importance where ship distortion is relevant and the latter when one is concerned with the rigid ship.

4. The rigid ship

The manoeuvring and control of a ship in calm water and with no wind might reasonably be expected to succumb fairly easily to rational analysis. In fact, the problem turns out to be highly nonlinear and one is even denied the implication of separating symmetric motions from antisymmetric. Forces exerted by the wind and waves serve only to complicate matters still further.

Of course, a great deal has already been achieved in manoeuvring theory. In this, considerable use has been made of model tests and frequently recourse is made to curve fitting techniques. It seems clear that, in this, very considerable skill has been brought to bear, for it is by no means obvious that this branch of ship dynamics stands in need of urgent attention. The fact remains that the scope for coherent theoretical studies appears to be enormous still.

Quite the reverse is true of seakeeping analysis. Here, the need for further research is both plain and urgent. So true is this indeed that there are regular international meetings devoted now to the subject of stability. The next, i.e. *Stability '90*, will be held in Naples later this year. Now the history of the study of ship stability is most interesting. As we have already noted, it started with linear quasi-static studies of metacentric height, proceeded to nonlinear hydrostatic studies and thence to dynamics.

It is widely believed that the object of stability analysis should be to describe the severe motions of a ship in waves and thence to deduce criteria for limiting those motions. This certainly appears to be a tenable point of view but conventional approaches do seem to raise serious questions in dynamics. Frequently one finds a study based on the premise that roll motions may be studied in isolation completely uncoupled from motions in other degrees of freedom. We would offer the tentative suggestion that the limitation of degrees of freedom in violent motions of a ship is something that should be approached with extreme caution.

Inevitably, perhaps, the study of violent seakeeping motions is normally thought to be governed by nonlinear equations. The prospect of studying random oscillations of large magnitude in a number of coupled degrees of freedom is somewhat daunting and the difficulty will be compounded when allowance has to be made for high winds. Unfortunately, the continuing heavy loss of life among trawlermen makes this a particularly bleak prospect.

Both manoeuvring theory and seakeeping theory refer to the response of a ship to external actions. In the manoeuvre, the ship responds to its rudder (or to differential use of propellers or to bow thrusters), while in seakeeping the ship is excited by waves on the surface of the sea. A third type of parasitic motion requires no applied excitation. This is the motion of *broaching to* in directional instability. It is quite well known that a ship's response to its rudder may depend heavily on the trim of the hull. Trim by the stern makes steering more difficult whereas trim by the bow can render a ship *touchy*. The combination of high speed, trim by the bow and shallow water (particularly when the hull has appendages forward like a bow rudder), can cause a ship to veer off course and roll heavily (Bishop *et al.* 1988). The prediction of such an outcome can only be made when sufficient hydrodynamic data are to hand and it has to be admitted that we have here a basic cause of concern in ship dynamics. Hydrodynamic actions can rather seldom be specified with much confidence. Hitherto, the prediction of directional instability has almost invariably been based (apparently adequately) on linear theory. That is to say, one seeks the condition under which a growing parasitic motion impends. Little point would be served by discussing the actual motion once broaching had started since the object must be not to let it happen.

This last point raises the question of whether or not the traditional study of seakeeping is well found. Is there much future in attempting to estimate large motions (particularly of roll) in seeking to devise rules for the prevention of capsize? The suggestion has been made that one need not study the actual motion to discover whether or not a ship will capsize. It may instead be sufficient to decide whether or not a ship is likely to become unmanageable. It has been suggested (Bishop *et al.* 1983) that it would be much more straightforward to investigate the possibility of a ship being both directionally unstable and potentially resonant in antisymmetric motions of which roll is a component, the resonant condition being that in the linear sense. This is admittedly a considerable break from traditional approaches but preliminary results are encouraging and, we suggest, something must be done soon about trawler losses. Certainly, one would not advocate trimming a trawler (or any other vessel) by the bow, yet there is no rule laid down forbidding that, so far as we are aware.

5. The flexible ship

Large ships have lower natural frequencies than small ones. Narrow band resonance distortion is therefore more likely to occur in large ships than in small ones, the sea being a comparatively low-frequency source of excitation. Large ships do not perform violent bodily motions but they do distort more. Now the distortions of a large ship are nothing like comparable with the significant dimensions of the hull. In other words, the distortions may validly be regarded as small.

It is very easy to show features of the dynamics of a rigid ship in which linear theory would be qualitatively wrong. The slowing down of a ship during a violent manoeuvre, and the performance of a form of limit cycle by a ship undergoing violent roll, are phenomena that could not be predicted with linear theory. So deeply committed to nonlinearity is the dynamics of the rigid ship, any suggestion that the dynamics of a flexible ship can reasonably be treated by linear means, is apt to provoke scepticism. Nevertheless, linear theory has begun to produce useful results and it is worthwhile to pause and consider whether or not linear theory is likely to be widely applicable.

So far as we are aware, no one has yet pointed out any qualitative defects in the linear theory of ship distortion. To discard linear theory merely because the results of using it appear to be inaccurate, therefore seems premature since potential sources of quantitative error are plain for all to see. It is for this reason linear theory has an important future in the dynamics of a flexible ship.

An important outcome of the application of linear theory is that one may distinguish between the symmetric and the antisymmetric motions of any ship which possesses port and starboard symmetry. For symmetric motion, one may refer to the generalized coordinates $p_0, p_1, p_2, p_3, p_4, \ldots$, representing generalized displacements of heave, pitch and successive distortion modes with respect to equilibrium axes. Alternatively, one may refer to the equations governing $p_0, p_1, p_2, p_3, p_4, \ldots$, representing sway displacement, roll angle, yaw angle, and successive deflections in modes of coupled bending athwartships and twist. So far as published results are concerned, it would appear that there has been a good deal of confusion about the nature of the modes to be used; the only unambiguous set known to the writers is that of the principal modes of the hull in the absence of water. Henceforth, therefore, we shall refer to the fluid actions on a ship as being essentially external forces.

The linear equations governing the sets of coordinates – either those of symmetric or of antisymmetric motions – may be written in the form (see, for example, Bishop & Price 1979)

$$(\boldsymbol{a}+\boldsymbol{A})\ddot{\boldsymbol{p}}+(\boldsymbol{b}+\boldsymbol{B})\dot{\boldsymbol{p}}+(\boldsymbol{c}+\boldsymbol{C})\boldsymbol{p} = \boldsymbol{\Xi}\,\mathrm{e}^{\mathrm{i}\omega_{\mathrm{e}}t}, \tag{1}$$

where

$$\boldsymbol{p} = [p_0, p_1, p_2, p_3, \ldots, p_N]^{\mathrm{T}} \tag{2}$$

and ω_{e} is the encounter frequency with sinusoidal waves. The square matrices of order $N+1$ fall into two groups: $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$, which represent the generalized structural *system matrices*, $\boldsymbol{a}$ being that of inertia, $\boldsymbol{b}$ being that of damping and $\boldsymbol{c}$ being that of stiffness. The matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ by contrast are those representing fluid actions proportional to the generalized acceleration, velocity and displacement respectively. The generalized quantity $\boldsymbol{\Xi}$ on the right-hand side is a column vector of order $N+1$ representing wave actions. Finally, the integer N represents the order of the last principal coordinate thought to be worthy of inclusion.

When it is remembered that, at least in some eyes, even the validity of equation (1) in practical ship dynamics is open to debate, one begins to see the sheer vulnerability of modern ship dynamics. Turning first to the structural system matrices, we note first that $\boldsymbol{a}$ and $\boldsymbol{c}$ are both diagonal matrices since the principal coordinates are being used, and that the generalized stiffnesses c_{rr} are related to the generalized masses a_{rr} by the simple result, $c_{rr} = \omega_r^2 a_{rr}$ where ω_r denotes the natural frequency of the dry structure. These generalized terms may be determined provided that the continuous structure can be adequately idealized into a discrete form and a suitable beam theory or finite-element analysis is readily at hand; but the best that is available for practical use is idealization on the basis of Timoshenko beam theory. While a supertanker is a very slender marine structure, the invocation of slender beam theory appears not to be without its hazards, particularly when one is thinking of antisymmetric bending, coupled with twisting the hull in which warping plays a significant part. While $\boldsymbol{a}$ and $\boldsymbol{c}$ are arguably 'the easy bit' dynamically, it is all too easy to exaggerate our ability to formulate them adequately.

The remaining structural system matrix $\boldsymbol{b}$ has its first m rows and columns null assuming m bodily motions, but the remaining square matrix of order $N-m+1$ is something that we know very little about. Indeed, but for the pioneering work of Kumai (1958), we should be almost without reliable evidence on this aspect. It is interesting to reflect that the change from riveted construction to welding may have made an enormous difference to this particular matrix and conceivably a large difference to ships' safety at sea as a consequence.

Turning now to the matrices, $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ representing the fluid actions, we come across an even more difficult area. The elements within them depend not only upon the shape of the hull and its operating conditions through the sea, but also on an independent variable λ. Suppose that the ship were operating in a flat calm sea, so that $\boldsymbol{\Xi} = \boldsymbol{0}$. The solutions for $\boldsymbol{p}(t)$ would be found as the complementary function of equation (1) and an appropriate solution of that equation would be

$$\boldsymbol{p}(t) = \boldsymbol{\Pi}\,\mathrm{e}^{\lambda t}, \tag{3}$$

where the quantity λ determines and is also partially determined by the elements of $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$. In other words, not only would the elements of the square matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ have to be known as functions of λ but also the trial solution (3) would have to be evaluated by some process of iteration; what is more, λ is a complex quantity. We are not aware of any literature in which this dependence is examined, either for symmetric or for antisymmetric motions of a ship.

For want of better, the elements of $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ are usually taken as being constants or as being dependent on forward speed and ω_{e}. This last possibility does at least mean that a particular integral of equation (1) can be found consistently. We are now, of course, in the province of the naval hydrodynamicist, and it is probably true to say that ship hydroelasticity is somewhat hampered by the sheer difficulty of his task.

It may be that it would be profitable to turn more to systematic experimentation with models. The planar motion mechanism, as it was originally conceived, was intended to measure slow motion derivatives but it seems quite clear that, suitably used, this oscillatory mechanism is of far greater importance. It can almost be thought of as a Fourier transform machine. Although this area of research is obviously wide open for development, it does seem possible that rigid and flexible models might be used to derive frequency dependent measurements that could provide the elements of the matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$. If this is the case, it might then be possible to obtain the inverse transforms of the Laplace transform. Some progress has been made with this type of work, but so far is of a very preliminary nature and is concerned solely with the numerical side and not the experimental.

Finally, the quantity $\boldsymbol{\Xi}$ in equation (1) is again essentially dependent upon work of the naval hydrodynamicist. Much progress has been made with strip theory but there remains the difficulty of deciding whether results so found are really adequate.

Linear theory has also been used in a slightly adventurous manner in the solution of slamming problems. It does not appear to be possible to tackle them with quite the same degree of rigour as one can less specialized problems of linear dynamics. Thus, if part of the hull is free of the water surface, there is some degree of empiricism in treating the hull as if its behaviour is governed by equation (1). Here again, then, there remains a great deal to be done. Incidentally, almost no work appears to have been published on the antisymmetric aspects of slamming.

Equation (1) governs the sinusoidal excitation arising from long-crested sinusoidal waves. From it, a particular integral may be found and such solutions may be assembled to give the random response to a random sea. The technique of summation is now quite well known. It has proved most helpful to calculate the response to a random sea (including the effects of slamming) in real time simulations. From the curve of the random responses, it is possible to deduce the corresponding curves of bending moment and shearing force (and in the antisymmetric case it would also be possible to deduce the variation of twisting moment). From the simulated curves of these responses, it is possible to proceed to stresses and so stress levels may be examined in the form of field stresses. It has recently been found that the traditional preoccupation with symmetric bending moment may be ill advised and that there would be merit in considering (field) principal stresses at various locations along the hull. Here again, analysis is still in its infancy.

6. Materials

Having used for so long such an apparently forgiving material as mild steel in construction of hulls, the naval architect may have been lulled into a sense of false security. More and more it is being found that cracking of steel plating is something that cannot be ignored. Rather little is said about the possibility of fatigue in the compendia of the 1960s, but cracking is now seen to be far more important than it was then.

It is interesting to speculate as to why this is so, for fatigue is far from a novelty in engineering. Cracking is to be expected where wave-induced stresses are high. Now, warship design involves the use of thin plating and these vessels are given a rough life at sea, with the result that stresses can be quite high. It is found that cracking does indeed occur but no serious losses on this score have been reported to our knowledge in recent years. The reason for this, we would hazard, is that a fatigue crack is likely to grow until it meets a bulkhead where it would be arrested. Now warships are divided up into many compartments and they are also subject to frequent examination and overhaul. Therefore cracking is likely not to pose a serious threat. A large bulk carrier, on the other hand, with its cavernous hull, is not such as to provide such crack stoppers. It seems that this may indeed be the reason why crack growth (which is likely to accelerate as the crack increases in size), is the probable cause of the high incidence of catastrophic losses of bulk carriers in recent times.

So it is that the ship dynamicist is likely to have to think more and more deeply about the metallurgical effects of the responses he finds. It is an unfortunate fact that the fatigue and crack propagation properties of even such a common-place material as mild steel are not well understood when the stressing is random and the surrounding medium corrosive.

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Of course, mild steel is not the only material of which ships are constructed nowadays. High tensile steel, aluminium and glass-enforced plastic are now commonly used in ship construction. Before their introduction, a great deal of effort was put into the naval architectural aspects of their use. While no doubt there remains much to be done where those materials are concerned, the overwhelming need must surely be to acquire better understanding of the limitations of mild steel and of the process of welding it.

7. Professional aspects

The time may have come when the standing of ship dynamics as an identifiable subject should be thought about. Traditionally, the ship designer and naval architect have accepted enormous responsibilities over hugh ranges of endeavour. No one would expect a naval architect to be an expert on the biochemistry of anti-fouling as well as, say, all the details of modern propeller design, as well as modern theories of responses to slamming, as well as... A line has to be drawn somewhere. It must surely be the case that a ship designer must be capable of understanding specialists in all the various specialist fields and, preferably be numerate in all of them as well. It seems to us that much the same must be said, not only of ship designers, but of other naval architects, notably those who classify, survey and oversee the actual construction of ships. It is simply not sensible to expect one person to be a specialist simultaneously in biochemistry, hydrodynamics, materials technology, structural theory, and so forth.

Whereas naval architects will nowadays take the advice of the paint manufacturers where anti-fouling is concerned. They will accept reassurances from steel manufacturers about the plating used in hulls, and so forth, they regard such matters as layout and ship handling as being their own special province of expertise. Where ship dynamics is concerned, naval architects do their best to keep up with modern progress by making a special study of the mechanics of ships. To illustrate this, figure 1 provides a schematic diagram of the relationship between naval architecture, solid mechanics and fluid mechanics. As previously discussed, to assess wave response, naval architects have to be able to describe the structure of the vessel and the fluid actions applied to it. The techniques required are the products of structural analysis and naval hydrodynamics and these have their origins in solid mechanics and fluid mechanics respectively and they are therefore formulated on the basis of experimentations and theoretical investigations of a classical sort. However, this does not imply that it is customary for naval architects to use methods they receive ready-made from physicists, applied mathematicians, etc. The techniques they use are often fashioned by fellow naval architects since there is a strong feedback from experience with actual ships, as indicated by the broken lines. Unfortunately, it is becoming more and more true that, in this, they tend to specialize either in the solid mechanics (---) or the fluid mechanics (-·-), and almost never in both. But ship dynamics is essentially concerned with both, so there is a growing problem. And when one remembers the pressures naval architects have been under in the past few years to diversify into offshore structures for example, one can see that this is beginning to be a serious matter. The dynamics of ships is in danger of becoming a somewhat vague and an unnecessarily empirical subject.

This is all too easy to illustrate, unfortunately. Thus great faith is placed nowadays in the concept of wave bending moment. This notion (which originated in the

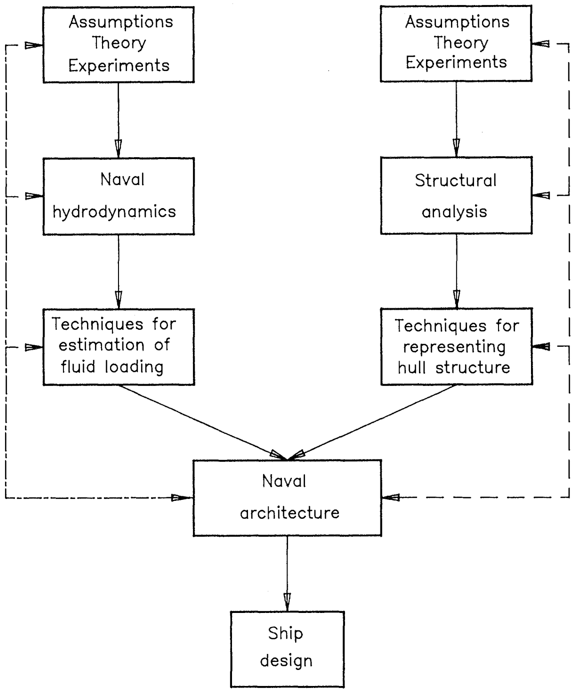

Figure 1. Schematic relationship between naval architecture, fluid mechanics (–·–) and solid mechanics (–––).

'rational' approach to ship stressing mentioned earlier) is very important indeed and has been adopted by the classification societies. But it is uncomfortably easy to find that it has not been properly understood and that attempts to 'correct' wave bending for the effects of 'springing' are based on a misapprehension (see, for example, Bishop 1989). The importance of this may well lie, not so much in the size of the correction (which, as it is conventionally misinterpreted, is usually small) but in the interpretation of stress data in fatigue analysis.

We would merely make the observation that more and more ship dynamics is becoming a matter for ship dynamicists. It is essentially a specialist business and means have got to be found for using more readily the results they find and the discoveries they make. If the professional naval architect is to remain a specialist for whom compendia like those referred to from the 1960s are fully understandable, then it is our view that those naval architects are going to have to think very hard about ways in which naval architecture is taught. For professional engineers of such broad understanding who make such important decisions, one does wonder if naval architecture is not something for the postgraduate or even the postdoctoral student.

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Discussion

G. Victory (*Surrey, U.K.*). In his presentation, and the humorous reference to 'falling off a log' Professor Price said the need arose for a supervisory authority for safety, and implied that this need was filled by the classification societies. In fact classification societies are commercial insurance organizations and are in competition with each other. Statutory responsibility for safety lies with the 'flag state'. However, some states, who have little or no survey organization of their own, delegate their statutory responsibilities to nominated classification societies, but it must be stressed that classification societies have no statutory authority for safety by right.