THE EFFECT OF MACHINERY IN WARSHIP DESIGN

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The main aim of the naval engineer is to provide machinery which will give to a ship the speed and endurance required by the Naval Staff, with those sterling qualities of reliability and so forth, discussed fully elsewhere. However, to pursue this aim alone would lead to technical stagnation, and the effectiveness and performance of our ships would not improve.

A measure of technical progress in ship design is the propulsion power required to achieve a certain speed and endurance with a certain payload of armament, equipment and men, etc.; it is only by reducing the power required that payload and performance can be improved.

Technical progress cannot be pursued without regard to cost, which is a function not only of the propulsion power required but also of machinery type and design. These two factors of cost are closely related, an obvious connection being the effect of machinery and fuel weight on propulsion power, through displacement. In practice a compromise must be reached between technical progress and cost.

In this article only technical progress will be considered, and it will be assumed that the main aim of the ship designer is to reduce propulsion power to a minimum. To do this it seems obvious that the size and weight, or displacement, of the ship should be reduced to a minimum; from this it follows that the weight of machinery and fuel should also be reduced to a minimum. However, this simple approach takes no account of the hull form of a ship, which also has a very important effect on the power required, and particularly so in warships, where speeds are high compared with merchant ships.

The effect of machinery on hull form will be discussed in this article, but first the effect on displacement will be examined beyond the obvious considerations leading to the minimum weight rule.

The machinery installation will be considered in a simplified way as a block having certain dimensions, weight and centre of gravity, requiring a certain quantity of fuel. Such details as the size of uptakes and position of funnels may have important effects, but their influence on propulsion is secondary.

DISPLACEMENT

The displacement of ships can be considered in two ways. Firstly, the Naval Staff in planning the future fleet have the choice of either several small ships or a lesser number of larger ships to deploy a certain number of different weapon systems. The owner of a merchant fleet has a similar choice to make related to a certain number of passengers or cargo capacity. Speed must also be selected. When these decisions have been taken, the ship designer is concerned with the power needed to meet the requirements of payload and speed, and will obviously attempt to reduce displacement to a minimum.

From the point of view of the Naval Staff or shipowner it is always more economical in power and fuel to build a small number of large ships rather

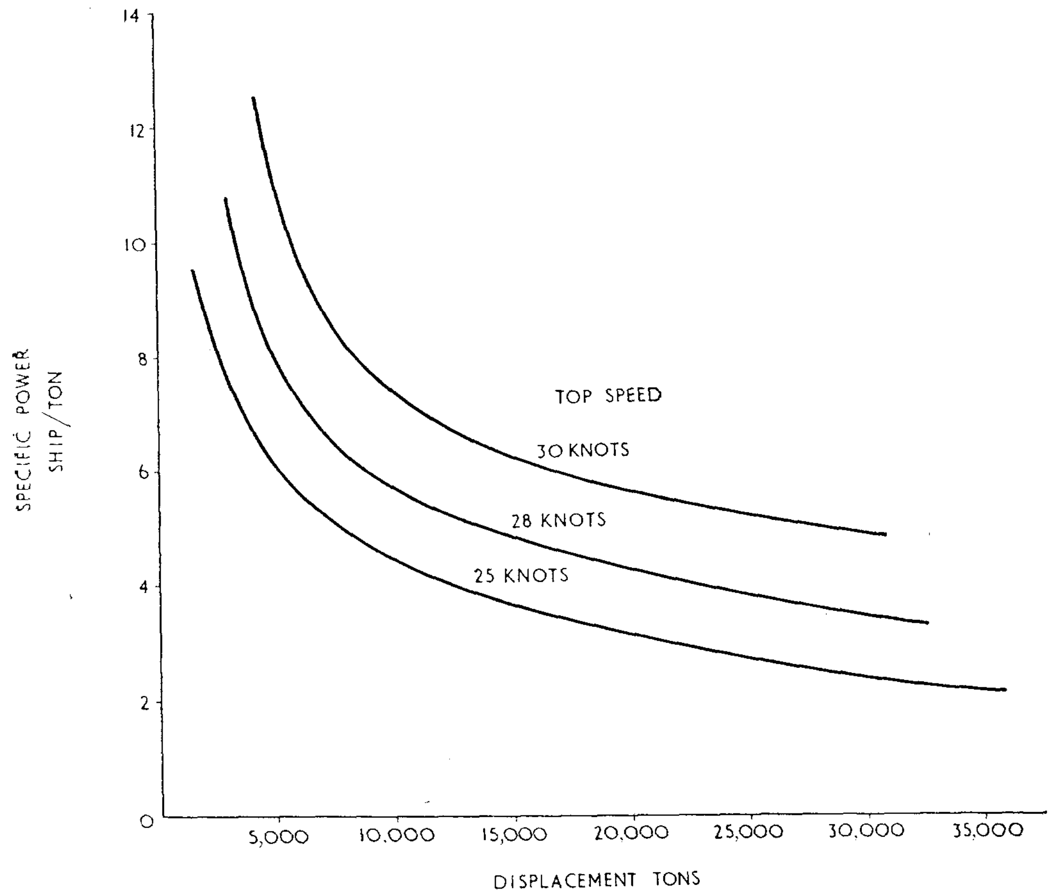


FIG. 1—SPECIFIC POWER IN SHIPS—VARIATION WITH SIZE

than a greater number of smaller ships. This is illustrated in FIG. 1, in which the power and displacement of modern warships have been correlated. FIG. 1 shows that, for a given top speed, the power required per ton decreases as the displacement increases. To take an example, a ship of 20,000 tons would need about 86,000 s.h.p. for 28 knots, whereas two ships of 10,000 tons each would require a total of 114,000 s.h.p., or 30 per cent more. FIG. 1 also illustrates the high cost in terms of power of relatively small increases in top speed. This size effect explains partly why the weight of propulsion machinery in large ships tends to be a smaller proportion of the displacement than in small ships.

For warships in particular it is also more economical to build a smaller number of large ships, not only for economy of installed power and fuel, but also for costs in general. However, other considerations peculiar to warships such as dispersion of risk, the provision of 'military presence' and the number of 'sensors' in many widely separated areas at one time make it impossible to give priority to economics.

From the point of view of the designer, power increases with displacement, and therefore the weight of hull structure, machinery and fuel should be kept as low as possible consistent with other requirements. Since the earliest days of mechanical propulsion the weight of armament, the speed and the endurance of warships have been generally increased as a result of lighter and more efficient machinery. The importance in the long term of reducing weight is generally accepted and finds expression in the simple rule that the weight of machinery and fuel should be reduced to a minimum.

During the design of a ship the advantage of saving weight must be viewed in relation to speed and displacement. In a ship designed for very high speed (say, 35 knots or more) the effect of weight changes will be very much greater than the effect in a ship with more modest speed (say, up to 30 knots). For example, a change in displacement of 10 per cent in a very fast ship would alter the power or speed by about the same proportion, i.e. 10 per cent, whereas the same change in a comparatively slow ship would alter the power by about 6 per cent only, or the speed by about 2 per cent only. One reason why weight changes do not affect propulsion in the same proportions at different speeds is the effect of the wave pattern generated round a ship, which alters considerably with speed.

The weight of machinery and fuel is usually between 20 and 35 per cent of the total displacement. The reduction of 10 per cent used in the example above would therefore require the considerable saving in machinery plus fuel weight of between 30 and 50 per cent, the necessary saving being greatest in proportion for the smaller weight of machinery plus fuel. It is evident that in large ships with modest speed the effect of saving machinery and fuel weight is unlikely to be very significant, whereas in small fast ships weight will probably be at a premium.

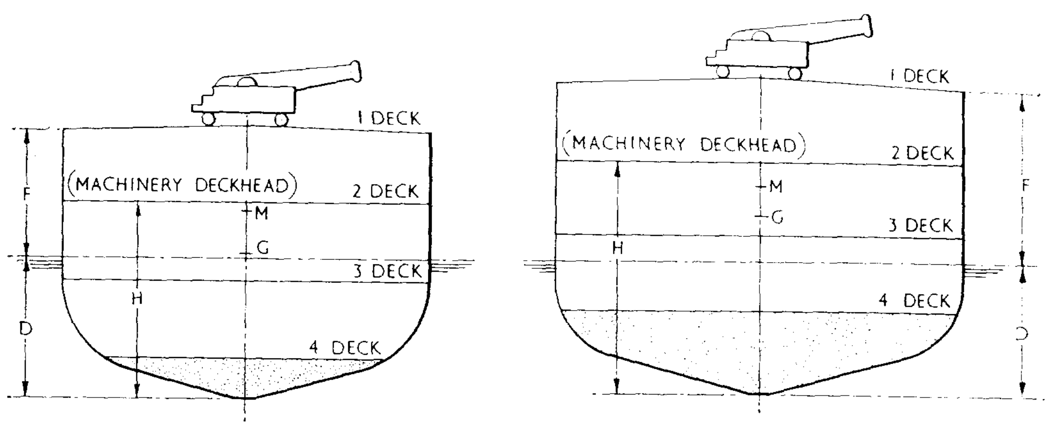
It is true that any weight saving during a design will reduce the power required, which in turn will reduce the weight of machinery and fuel, and so on. However the secondary saving of power and weight is small compared with the initial change because the rate of change of power with weight is naturally enough very much greater for propulsion machinery than it is for the ship as a whole: the specific power of machinery is very much greater than the specific power required to drive the ship, expressed in horsepower per ton displacement. It must also be remembered that a large proportion of the total weight of machinery and fuel is independent of propulsion, being associated with ship services such as electrical power. In modern warships the weight of machinery services other than propulsion is considerable, and is increasing steadily with new designs.

A law of diminishing returns applies to weight saving. As the weight of machinery and fuel becomes a smaller proportion of displacement, the advantages of saving weight decrease, and it becomes increasingly difficult to make further significant reductions. However, in the long term reductions of machinery weight and improvements in efficiency are absorbed by increased armament or performance, and therefore there will always be a strong incentive for saving weight and improving efficiency.

HULL FORM

For good propulsion, the leading dimensions of a ship should be related in certain ratios; for example, the length should be about ten times the beam. These ratios occur because resistance is a function of two components, one of which increases with length while the other decreases with length, giving some ratio at which resistance is a minimum; these components are skin friction resistance and wavemaking resistance respectively. In practice the optimum ratios can seldom be achieved for reason of stability; they may also be unsuitable for other ship-design reasons. The length-to-beam ratio in particular is usually less than the optimum for propulsion.

As a result there is usually less incentive to reduce the length of the main machinery compartments than there is to keep width or height within specified limits, because a reduction in length on its own is unlikely to improve propulsion. A reduction in length will also tend to increase draught and reduce freeboard, and will reduce the area of the weather decks available for weapons and aerials. In attempting to reduce the space occupied by the machinery installation it is usually width rather than length which is critical.



M = Metacentre
G = Centre of gravity
F = Freeboard

D = Draught
H = Deckhead height in machinery compartments

FIG. 2—EFFECT OF DECKHEAD HEIGHT IN MACHINERY COMPARTMENTS (SMALL SHIP)

The deckhead height used in the machinery compartments may have major influence on hull form; this rather unexpected effect will be discusse later in detail.

The main factor which determines whether the designer can achieve a goo propulsive form is the distribution of weight within the ship. It is an axior of ship design that a good hull form cannot be achieved unless the centre o gravity is low. It is becoming increasingly difficult to achieve a low c.g. toda as the weight of weapons, aerials and associated equipment is increased, becaus these must invariably be placed high in the ship.

It is always possible to achieve adequate stability, either by raising th metacentre by increasing beam or by using a fuller form, or, alternativel by lowering the c.g. with ballast; in surface ships these measures increas resistance, and are generally considered undesirable. However the specifie requirements for a ship may make it impossible to avoid such expedients.

The influence of the machinery installation on the c.g. of the ship is probabl the most important effect of machinery in warship design today. Feature affecting the c.g. are:—

(*a*) The weight and c.g. of the machinery and fuel

(*b*) The deckhead height in the machinery compartments.

The effect of (*a*) is self-evident. The greater the weight of machinery and fuel and the lower its c.g., the greater the moment assisting stability, because thei c.g. invariably lies below the metacentre. For a constant weight of machiner plus fuel, the c.g. of a light machinery installation requiring a large quantit of fuel will be lower than that of a heavy but more efficient installation requirin less fuel, other factors being equal. However fuel saving has considerabl logistic merit in itself; also it may be difficult to accommodate large quantitie of fuel in a design, and extensive water ballasting may be necessary to ensur stability after a relatively short period at sea.

The effect of deckhead height on the c.g. of the ship is illustrated in FIG. 2 equipment high in the ship has been represented by a cannon. It can be seer that an increase in height gives a corresponding increase in the height of al equipment and structure above the deckhead, and a corresponding increas in the height of the c.g. The figure is intended to show the effect in a smal ship, and is somewhat exaggerated. In a large ship where the height of machiner compartments is a relatively small proportion of the total height of the ship the effect will clearly be less marked.

So far as stability is concerned, the deckhead of the main machinery compartments should be as low as possible. However, many other important factors are involved, and it may be difficult to lower the deckhead below a certain level, even if machinery would make this possible. These factors are:—

(*a*) Deck area

(*b*) Fuel stowage

(*c*) Freeboard

(*d*) Draught.

In FIG. 2 beam has been adjusted to retain the same metacentric height GM for both ships, and draught has been adjusted to keep the same displacement (or cross-sectional area in the figure). It can be seen that the ship with greater deckhead height is superior in many respects, in that the area of decks is greater, fuel stowage space is greater, and freeboard is also greater, which would probably give better seakeeping qualities. Draught is also less, though this may not be an advantage. These changes are partly the result of keeping the same separation between decks, which is usually about eight feet. It is of interest that the height of the average man, which fixes the deck height necessary, is a significant factor in ship design.

It is often convenient to extend the top of compartments locally by the height of one deck to accommodate such items as boiler economizers. This is usually preferable to raising the general height of the machinery compartments, though valuable space is lost above, and deck strength is reduced.

It is convenient at this point to consider the stowage of fuel in more detail. The compartments between the lowest deck and the hull are ideal for the stowage of liquids, and this assists stability. Indeed it would be difficult to use such compartments for any other purpose, due to their sub-division by major hull members, and their awkward shape, particularly towards the bow and stern. A few must be reserved for trimming and fresh water, but the majority provide a convenient stowage for fuel.

If the fuel quantity exceeds the volume of these bottom compartments, then some tanks must be extended by the height of one deck to form 'deep' tanks. These encroach upon the usable area of the lowest deck, and also raise the centre of gravity of the fuel. However in many warships the demand for space high in the ship is so great that there is often space below which cannot be used effectively; a possible solution is to use this space for fuel stowed in deep tanks; this is also welcome from the engineering point of view, because a small number of deep tanks are more convenient than a greater number of double-bottom tanks.

In ships of about 5,000 tons and over, double-bottom compartments are usually provided under the machinery spaces to give greater protection, and also to stow large quantities of fuel without encroaching unduly upon the area of the lowest deck. DB fuel tanks under machinery spaces also help to achieve a low c.g., provided that the deckhead is not raised as a result.

To summarize, the centre of gravity of machinery and fuel should be as low as possible so that adequate stability can be achieved without recourse to measures which increase ship resistance. The engineer should also attempt to reduce the height of an installation so that a low deckhead could be used if other ship design factors make this possible.

THE DESIGN PROCESS

Research and development create the technical climate or 'state of the art' in which a ship design is conceived. There is seldom time or sufficient resources to carry out a major research or development programme successfully for one class of ship, and the designer is therefore restricted from the beginning by the prevailing technical climate. The naval engineer can exert only a limited influence on this, because the very much larger commercial market can usually give industry a more continuous and reliable profit without the problems associated with military requirements.

At the stage where research and development are not directed towards a particular ship design, the aims of the designer are simple and obvious—light, compact and efficient machinery is required. At this stage it is not possible to say that a particular item or type of machinery could give better ship design than any other. However all technical developments which offer low weight, small size or high efficiency must clearly be pursued so that should a suitable application arise, the innovation can be incorporated without misgiving. Conversely, a particular development may make it possible to achieve greater armament, speed or endurance, and the development itself may then generate a suitable application.

When the requirements for a ship have been formulated, the design process enters a new and more specific stage during which a ship is committed to a machinery installation of a particular type and disposition. The extremely complicated subject of machinery selection must be confined to ship design aspects in this article but, as stated in the introduction, less tangible factors such as cost, reliability and maintenance may be of equal or greater importance. Ship design aspects may be of secondary importance only in the machinery selection process.

In some warships the selection of machinery type presents little problem, because the requirements for the ship and prevailing technical climate make the selection of a particular type almost inevitable; very small and very large warships often come into this category. Between these extremes of size, several alternative installations may appear suitable for a ship; before ship design aspects are considered in detail it must obviously be established which alternatives could be achieved with reasonable certainty in the limited time available.

To establish with reasonable certainty which machinery installation would give the best ship, it would be necessary to develop a series of complete ship designs using each alternative. To give a valid solution, the design of both ship and machinery would have to be taken to a stage where further significant changes would be unlikely during the design and building of the ship. In practice large changes occur almost inevitably as a design is developed; this is due partly to modified requirements and partly to difficulty in predicting the end product of many complicated and related variables. Machinery type must often be selected before other features of the ship design have been established. The method of comparative ship-design studies can seldom give really valid and accurate results on which the selection of machinery can be based with complete confidence. Even when a ship has been completed it cannot be proved that the machinery installation used was in fact more suitable than some other possibility.

This rather unsatisfying and nebulous situation has been discussed at some length to show that even when tangible ship design factors are considered, machinery selection is very much a matter of professional judgment and opinion. In practice, where several alternatives appear suitable, a comparative study must be carried out in as much detail as time and effort permit; it is recognized that this can only give a rough indication of ship design effects.

Once a type of machinery has been chosen, and major features such as unitization have been decided, the objectives of the designer become very much clearer. Machinery layout and component design must inevitably be decided mainly from engineering considerations, but the designer must also make every effort to keep the centre of gravity as low as possible to assist the ship design; this is in fact the only rule which can be followed without reservation once the main features of the machinery installation have been chosen. Attempts to achieve a low c.g. will clearly start with the largest and heaviest items, such as main engines, gearing and boilers. Factors which determine their overall height and vertical position in the ship must firstly be identified, and then examined with a view to lowering them as much as possible. Not only will this lower their c.g., but it will also enable the naval architect to lower the deckhead in the machinery spaces, and thus the c.g. of the equipment and structure above, if other features of the ship should make this possible. Of the remaining smaller items, the heaviest should clearly be placed as low as possible.

It follows from the 'c.g. rule' proposed above that the weight of items above the metacentre should be reduced as much as possible to aid stability. The weight of items high in the ship is usually small compared with the total machinery weight, and therefore the weight which can be saved on such items is probably small; however, there may be a considerable improvement in stability as a result.

When the weight of items below the metacentre is considered, a conflict of interests arises. The greater part of the installation lies below the metacentre, and the scope for saving weight will be greatest here; on the other hand, weight saved will detract from stability. To minimize this adverse effect on stability, efforts to reduce the weight of items below the metacentre should vary directly with their height in the ship.

SUMMARY AND CONCLUSIONS

To improve the performance and payload of warships, the power required for propulsion must be reduced. Propulsion power depends not only on the displacement of the ship but also on the form of the hull; machinery has a significant effect on both.

The effect of machinery and fuel on displacement is direct and self-evident, and gives rise to the simple rule that the weight of machinery plus fuel should be reduced to a minimum, subject to engineering requirements. In general research and development, where no specific ship design is being considered, the effect of a particular item or type of machinery on hull form cannot be predicted and therefore, so far as ship design in general is concerned, only broad objectives such as light weight, small size and high efficiency can be pursued.

During the design of a ship, the advantage of saving weight must be viewed in relation to possible gains in performance, as the 'payload' is fixed at the start by the Naval Staff. Also weight cannot be considered at this stage in isolation from other features of a complete machinery installation, such as compartment dimensions and centre of gravity, which also affect propulsion and other important features of ship design.

In modern warships, with very heavy weapons and aerials mounted high in the ship, the machinery and fuel provide a valuable stabilizing moment. The naval architect always can, and will, provide adequate stability, but this may entail measures which increase propulsion power. Machinery and fuel must therefore provide the greatest stabilizing moment possible with the least weight, to reduce propulsion power to a minimum. This difficult requirement gives rise to a possible design rule, described here as the 'C.G. Rule':—

'Subject to engineering requirements, the centre of gravity of a machinery installation should be as low as possible. To this end all machinery should be placed as low as possible, priority being given to the heaviest items.

The weight of machinery above the metacentre should be reduced to a minimum; efforts to reduce the weight of items below the metacentre should vary directly with their height in the ship, to minimize the detrimental effect of saving weight on stability'.

The c.g. of the ship depends in part on the deckhead height used in the machinery compartments; for stability this should be as low as possible, but other ship design factors may make this unsuitable. A machinery installation should therefore be as low as possible, so that a low deckhead could be used if other ship design factors make this possible.

In the process of selecting a machinery installation, ship design aspects may be of secondary importance only. However, the purely technical aim should be to reduce propulsion power to a minimum. Ship design implications can only be established by developing the design of both ship and machinery together, ideally to the stage where further change is unlikely. Unfortunately this is seldom possible, and ship design aspects of machinery selection, like every other aspect, are very much a matter of professional judgement and opinion.

There is therefore a strong element of art as well as science in ship design and it is hoped that this article takes the effect of machinery in warship design beyond the comforting cliché that all design is a compromise.