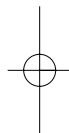
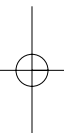
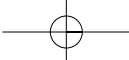


Introduction to Naval Architecture



Introduction to **Naval Architecture**

Fourth Edition

E. C. Tupper, BSc, CEng, RCNC, FRINA, WhSch



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Preface to the fourth edition

The changes in this edition, compared with the third edition, published in 2000, reflect the feed back received from those using the book. They include a general revision of the arrangement of the text and take account of the continuing advances in our knowledge in the field of naval architecture and the way naval architects approach their work. There is greater emphasis on the work of national and international regulatory organizations and of the classification societies. Safety and environmental pollution receive more attention in line with the growing public concerns in these matters and their impact upon ship design and operation, for instance, the double hull tankers. In the areas of manoeuvring, directional stability and vibration some of the mathematics has been replaced by a physical explanation of the phenomena concerned. The discussion on different ship types has been made broader reflecting the greater diversity of designs within any one ship type.

Although some maritime authorities still use the old units, SI units are now almost universal. Those who do not use them every day are generally familiar with them and for these reasons only SI units are used in the main text. To assist those who may wish to consult data in the old form conversion tables are given in an appendix. As a special case, and because of the importance of the early work in ship resistance, the reader is introduced to the Froude notation in another appendix.

It is hoped that these changes will make the book more suitable for those who need only a relatively simple introduction to naval architecture and will provide a better understanding for those students who do not find mathematical equations easy to interpret. In any case the mathematics cannot, in a book at this level, be rigorous. Even with advanced texts and research papers, simplifying assumptions are often necessary. For instance, problems are often treated as linear when, in reality, many aspects of a ship's behaviour are non-linear. The book should also help an experienced person refer quickly to the main factors to be considered in common situations.

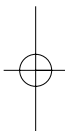
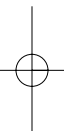
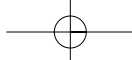
As in so many areas of modern life the computer is becoming an ever more powerful tool. More has been said upon the part it plays in the

design, production and operation of ships but it would be unrealistic to attempt any detailed discussion of the many programs available to the naval architect. These programs are changing rapidly and the student is referred to the regular CAD/CAM reviews and updates which appear in the journals of the learned societies. The use of spreadsheets for many of the repetitive calculations is illustrated. Solutions to the questions are available from the Elsevier website. Appendix E presents a range of questions based on each chapter of the book for use by students and lecturers, who may choose to set the questions as homework or self-study exercises. See Appendix E for further information.

References have been updated to help the reader follow up, in more detail, the latest developments in naval architecture. This aim of keeping up to date, however, is best achieved by joining one of the learned societies, which usually allow free, or much reduced cost, membership for students.

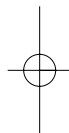
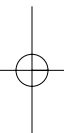
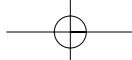
Recognizing the increasing amount of information becoming available on the Internet, the opportunity has been taken to include some useful web site addresses. As an example the web site for Elsevier Butterworth-Heinemann would be given as (<http://books.elsevier.com>). Many other useful sites can be gleaned from the technical press. The student is encouraged to use these sources of data but they need some fundamental knowledge of the subject before they can be used intelligently. It is hoped this book provides that understanding.

**Dedicated to
Will, George, Phoebe and Millie**



Acknowledgements

Many of the figures and most of the worked examples in this book are from *Muckle's Naval Architecture* which is the work this volume replaced. A number of figures are taken from the publications of the Royal Institution of Naval Architects. They are reproduced by kind permission of the Institution and those concerned are indicated in the captions. I am very grateful to my son, Simon, for his assistance in producing the new illustrations.



1 Introduction

SHIPS

Ships are still vital to the economy of many countries and they still carry some 95 per cent of world trade. In 1998 the world's cargo fleet totalled some 775 million tonnes deadweight and was increasing by 2 per cent a year (Parker, 1998). The average deadweight was about 17 000. Although aircraft have displaced the transatlantic liner, ships still carry large numbers of people on pleasure cruises and on the multiplicity of ferries in all areas of the globe. Ships, and other marine structures, are needed to exploit the riches of the deep.

Although one of the oldest forms of transport, ships, their equipment and their function, are subject to constant evolution. Changes are driven by changing patterns of world trade, by social pressures, by technological improvements in materials, construction techniques and control systems, and by pressure of economics. As an example, technology now provides the ability to build much larger, faster, ships and these are adopted to gain the economic advantages they can confer.

A feature of many new designs is the variation in form of ships intended for relatively conventional tasks. This is for reasons of efficiency and has been made possible by the advanced analysis methods available, which enable unorthodox shapes to be adopted with confidence in their performance. The naval architect is less tied to following a type ship. In the same way means of propulsion and steering are tailored to suit the hull form and conditions of service, and they will be closely integrated one with the other.

NAVAL ARCHITECTURE AND THE NAVAL ARCHITECT

Before going further, and to set the scene for this book, it is necessary to ask:

- What is naval architecture?
- What is required of a naval architect?

The full answer to each question is complex but, in essence, one can say:

- Naval architecture is the science of making a ship ‘fit for purpose’.
- A naval architect is an engineer competent in naval architecture.

It remains to see what is meant by ‘ship’ and ‘fit for purpose’.

The ship

This term must be interpreted broadly and can refer to any structure floating in water. It is usually self-propelled but some, for instance, dumb barges and some offshore structures rely on tugs to move them. Others rely on the wind. Marine structures, such as harbour installations, are the province of the civil engineer.

The purpose of a merchant ship is to carry goods, perhaps people, safely across water. That of a warship is the support of government policy in the international field. Let us concentrate on the merchant ship. In ordering a new vessel the owner will have in mind, *inter alia*:

- a certain cargo;
- a certain volume of cargo to be carried on each voyage;
- a range of ports from which the ship will operate;
- an average journey time.

Each requirement will have an impact upon the ship design:

- The type of cargo may be able to be carried in bulk or may require packaging; it may be hazardous or it may require a special on-board environment.
- The volume of cargo will be the major factor in determining the size of the ship. An additional factor may be the need to move the cargo in discreet units of a specified size and weight.
- The ports, plus any rivers and canals to be negotiated, may place restrictions on the overall dimensions of the vessel. Depending on the port facilities the ship may have to provide more, or less, cargo handling equipment on board. The ports will also dictate the ocean areas to be traversed and hence the sea and weather conditions likely to be encountered.
- Ship schedules will dictate the speed and hence the installed power. They may point to desirable intervals between maintenance periods.

Fit for purpose

To be fit for purpose a ship must cater for the above and be able to operate safely and reliably. There are many national and international rules and regulations to be met. Briefly the ship must:

- Float upright with enough watertight volume above the waterline to cope with waves and accidental flooding.
- Have adequate stability to cope with operational upsetting moments and to withstand a specified degree of flooding following damage. It must not be so stable that motions become unpleasant.
- Be able to maintain the desired speed in the sea conditions it is likely to meet.
- Be strong enough to withstand the loads it will experience in service.
- Be capable of moving in a controlled way in response to movements of control surfaces; to follow a given course or manoeuvre in confined waters.
- Not respond too violently to waves.

The ship must do all this economically, safely, reliably and with the minimum size of crew. The list of contents shows that this book deals with these matters in turn. The knowledge gained is brought together in discussing the design process and the different ship types that emerge from an application of a common set of principles. The design should be flexible because requirements are likely to change over the long life expected of ships. History shows that the most highly regarded ships have been those able to adapt with time.

Variety

Naval architecture is a fascinating and demanding discipline. It is fascinating because of the variety of floating structures and the many compromises necessary to achieve the most effective product. It is demanding because a ship is a very large capital investment and because of the need to protect the people on board and the marine environment.

A visit to a busy port reveals the variety of forms a ship may take. This is due to the different demands on them and the conditions under which they operate. There are fishing vessels ranging from the small local boat operating by day to the ocean going ships with facilities to deep freeze their catches. There are vessels for exploitation of undersea energy sources, gas and oil, and extraction of minerals. There are oil tankers, ranging from small coastal vessels to giant supertankers. Other huge ships carry bulk cargoes such as grain, coal or iron ore. Ferries carry passengers between ports which may be only a few kilometres or a hundred

apart. There are tugs for shepherding ships in port or for trans-ocean towing. Then there are dredgers, lighters and pilot boats without which a port could not function. In a naval port there will be warships ranging from huge aircraft carriers through cruisers and destroyers to frigates, patrol boats, mine countermeasure vessels and submarines.

Increasingly naval architects are involved in the design of small craft such as yachts and motor cruisers. This reflects partly the much greater number of small craft, mostly for leisure activities; partly the increased regulation to which they are subject requiring a professional input and partly the increasingly advanced methods used in their design and new materials in their construction. However, in spite of the increasingly scientific approach the design of small craft still involves a great deal of 'art'. Many of the craft are beautiful with graceful lines and lavishly appointed interiors. The craftsmanship needed for their construction is of the highest order.

Over the last half century many naval architects have become involved in offshore engineering – the exploration for, and production of, oil and gas. Their expertise has been needed for the design of the rigs and the many supporting vessels, including manned and unmanned submersibles which are increasingly used for maintenance. This involvement will continue as the riches of the ocean and ocean bed are exploited more in the future.

For ships themselves there is considerable variety in hull form. Much of this book is devoted to single hull, displacement forms which rely upon displacing water to support their full weight. In some applications, particularly for fast ferries, multiple hulls are preferred because they provide large deck areas with good stability without excessive length. Catamarans have been built in large numbers. The idea is far from new as many societies have made use of outriggers to provide increased safety. As early as the 1870s two twin hull ships of 90 m length were used on the cross channel route between Dover and Calais. Although overtaken by other developments both ships had good reputations for seakeeping. More recently trimaran and pentamaran designs have been proposed and the *Triton*, a trimaran demonstrator, has been very successful on trials.

In planing craft high speeds may be achieved by using dynamic forces to support part of the weight when under way. Surface effect ships use air cushions to support the weight of the craft, lifting it clear of the water. This is particularly useful in navigating areas with sand banks and in providing an amphibious capability. Hydrofoil craft rely on hydrodynamic forces on submerged foils under the hull to lift the main part of the craft above the waves. Other craft, particularly on rivers in Russia, lift is gained by the so-called wing-in-ground effect (WIG). There are, of course, many examples of hybrid craft incorporating several of the above features.

Some of the more specialized craft are dealt with in a little more detail in the chapter on ship types.

Variety is not limited to appearance and function. Different materials are used – steel, wood, aluminium, reinforced plastics of various types and concrete. The propulsion system used to drive the craft through the water may be the wind but for most large craft is some form of mechanical propulsion. The driving power may be generated by diesels, steam or gas turbine, some form of fuel cell or a combination of these. Power will be transmitted to the propulsion device through mechanical or hydraulic gearing or by using electric generators and motors as intermediaries. The propulsor itself is usually some form of propeller, perhaps ducted, but may be water or air jet. There will be many other systems on board, such as means of manoeuvring the ship, electric power generation, hydraulic power for winches and other cargo handling systems, and so on.

A ship can be a veritable floating township of several thousand people remaining at sea for several weeks. It needs electrics, air conditioning, sewage treatment plant, galleys, bakeries, shops, restaurants, cinemas and other leisure facilities. All these, and the general layout must be arranged so that the ship can carry out its intended tasks efficiently. The naval architect has not only the problems of the building and town designer but a ship must float, move, be capable of surviving in a very rough environment and withstand a reasonable level of accident. It is the naval architect who ‘orchestrates’ the design, calling upon the expertise of many other professions in achieving the best compromise between many, often conflicting, requirements. The profession of naval architecture is not only engineering, it is an art as well. The art is in getting a design that is aesthetically pleasing and able to carry out its function with maximum effectiveness, efficiency and economy. The naval architect’s task is not limited to the design of ships but extends into their building and upkeep. These latter aspects are not covered in any detail in this book.

Naval architecture is a demanding profession because a ship is a major capital investment taking many years to create and expected to remain in service for 25 years or more. It is usually part of a larger transport system and must be properly integrated with the other elements of the overall system. A prime example of this is the container ship. Goods are placed in containers at the factory. These containers are of standard dimensions and are taken by road, or rail, to a port with specialized handling equipment where they are loaded on board. At the port of destination they are off-loaded on to land transport. The use of containers means that ships need spend far less time in port loading and unloading and the cargoes are more secure. Port fees are reduced and the ship is used more productively.

Most important is the safety of ship, crew and, increasingly nowadays, the environment. The design must be safe for normal operations and

not be unduly vulnerable to mishandling or accident. No ship can be absolutely safe and a designer must take conscious decisions as to the level of risk judged acceptable in the full range of scenarios in which the ship can expect to find itself. There will always be a possibility that the conditions catered for will be exceeded. The risk of this and the potential consequences must be assessed and only accepted if they are judged unavoidable or acceptable. Acceptable, that is, by the owner, operator and the general public and not least by the designer who has ultimate responsibility. Even where errors on the part of others have caused an accident the designer should have considered such a possibility and taken steps to minimize the consequences. For instance, in the event of collision the ship must have a good chance of surviving or, at least, of remaining afloat long enough for passengers to be taken off safely. This brings with it the need for a whole range of life saving equipment. The heavy loss of life in the sinking of several ferries in the closing years of the 20th Century show what can happen when things go wrong.

Cargo ships may carry materials which would damage the environment if released. The consequences of large oil spillages are reported all too often. Other chemicals pose even greater threats. In the case of ferries, the lorries on board may carry dangerous loads. Clearly those who design, construct and operate ships have a great responsibility to the community at large. If they fail to live up to the standards expected of them they are likely to be called to account. Over the years the safety of life and cargo has prompted governments to lay down certain conditions that must be met by ships flying their flag, or using their ports. Because shipping is world wide there are also international rules to be obeyed.

It will be clear from what has been said above, that naval architects must work closely with those who build, maintain and operate the ships they design. This need for teamwork and the need for each player to understand the others' needs and problems, are the themes of a book published by The Nautical Institute in 1999.

THE IMPACT OF COMPUTERS

Computers have made a great impact upon the lives of everybody. They have had considerable impact upon the design, production and operation of ships. Their impact is felt in a number of ways:

- (1) Individual calculations are possible which otherwise could not be undertaken. For instance, ship motion predictions by theory and the use of finite element analysis for structural strength. Design optimization techniques are increasingly being proposed and developed.

- (2) A number of programs can be combined to form a computer aided design system where the output from one program provides a direct input into others. Revisions of the database as the design develops can be used to up-date automatically the results of calculations carried out earlier. Thus changes in scantlings occasioned by the strength calculations can up-date displacement and stability estimates. The end result of the hull fairing process leads to a tape which can be supplied to the shipbuilder instead of the lines plan and table of offsets.
- (3) More data is immediately available to the designer to assist in decision-making.
- (4) Many more design options can be studied and compared and these can be at an earlier stage in design and in greater detail.
- (5) Simulations can be produced of what the finished ship will look like, internally as well as externally. These can be used instead of mock-ups to assist in achieving efficient layouts. The colours and textures of different materials can be shown. An owner can effectively be taken for a walk through his ship before it leaves the drawing board (Thornton, 1992).
- (6) In production the computer can help with routine matters like stock control. It can control cutting and welding machines ensuring greater accuracy of fit and facilitating more extensive pre-fabrication and reducing built-in stress levels.
- (7) On board it can control machinery and monitor its performance to give early warning of incipient failure.
- (8) It can help the command with decision-making. For instance, it can advise on loading sequences to eliminate the possibility of overloading the structure. It can assist warship captains when under enemy attack by suggesting the optimum actions to take in defence.
- (9) Computer-based simulators can assist in training navigators, machinery controllers and so on.

It is hoped that these few paragraphs have shown that naval architecture can be interesting and rewarding. An example of the variety and interest to be found in the profession can be obtained by reading the memoirs of an eminent naval architect, Marshall Meek (2003). The various topics mentioned above are discussed in more detail in later chapters where the fundamental aspects of the subject are covered. The references given at the end of the book, arranged by chapter, indicate sources of further reading for following up specific topics. A more advanced general textbook, for instance by Rawson and Tupper (2001), can be consulted if desired. This has many more references, together with worked and set examples, to assist the interested reader. For comments on sources and references see Appendix A.

2 Ship design

This chapter sets the scene for the rest of the book. By discussing the design of ships in general terms the importance of their various attributes becomes clear. Those which are the concern of the naval architect are then dealt with in more detail in later chapters.

A modern ship is very expensive to build and is expected to operate efficiently over a long time span, often in excess of 25 years. Unlike other forms of transport there are no prototypes. Even with a class of ships, the first of that class is expected to be commercially useful from the date of acceptance into service. This places a great responsibility on the designer to 'get things right'. In the early days of design it is relatively easy, quick and cheap to introduce changes. Thus time spent early on in looking at a wide range of options is time well spent. It is, of course, for the prospective owner to say what is needed so the starting point is a good set of *requirements*.

THE REQUIREMENTS

A set of well specified requirements will define the operational *capabilities* a ship should possess. Thus capabilities might be the ability to maintain a speed of 20 knots in the average sea conditions it is likely to meet on its usual service run; the ability to carry 500 standard containers or the ability to carry 1000 passengers. The statement of requirements should be couched in operational terms as that represents the concern of the operator and the requirements should be as clear as possible. Unless they are, there is no yardstick by which it can be judged whether the needs have been met. This is a weak contractual position, besides making life more difficult for the designer. As far as possible, how the capability is provided should be left to the designer. Thus it is the designer who should propose how best to achieve the speed capability. For instance, what is needed in the way of:

- total installed power;
- type of main engine – steam, diesel, gas turbine;

- how many shafts, or whether azimuthing pods are used;
- type of propeller; fixed or controllable pitch, ducted;
- shaft revolutions.

The designer must work closely with the owner in deciding many of these issues as the owner will often have a legitimate interest in the decisions made. In the case of the main propulsion plant, for instance, the new ship may be joining a fleet which to date has been exclusively diesel driven. If the new ship goes over to gas turbine drive the owner will have to arrange for retraining of the engine room staff and will face additional logistics problems in providing spares. It is sometimes considerations of this sort that lead to the industry getting an undeserved reputation for being unwilling to introduce change.

In addition to meeting an owner's requirements there are a wide range of international and national regulations to be met and standards which may originate with the owner or builder. The regulations are touched upon in the next chapter. They represent minima which good operators will often choose to exceed. The standards may relate to the levels of accommodation to be provided for crew and passengers.

As decisions are made on how best to meet the stated requirements the ship gradually takes shape. Its size, layout and the equipments to be fitted will emerge. Everything in the ship must serve a useful purpose. Thus:

- The machinery must provide enough power to achieve the desired speed.
- Hoisting gear of a certain capacity will be needed to load and off-load the cargo. Here the facilities in the ports the ship is to use must be taken into account.
- The hull, with its sub-division, must provide a safe vehicle for the intended service. For instance it may need to be strengthened if the ship is to operate in ice.
- The electrical system must provide adequate power for all machinery to be run, allowing for the fact that not all of the installed equipments will be needed at the same time. For instance, cargo handling gear may only be needed in port.

Margins, in the form of extra capacity and/or redundancy will be needed to allow for changes during the service life and to provide the desired level of availability of any function.

In the case of warships the government, as represented by the navy, or Ministry of Defence, is effectively the owner. It is the naval staffs who specify what is needed to enable the navy to meet its commitments in support of the country's foreign policy.

DESIGN

The designer will usually find that there are significantly different ways of meeting the requirements and the 'best' must be chosen. Best is placed in quotation marks because what is meant by this is a matter of judgement. Design is always a compromise in which one aspect of performance can be improved at the expense of some other feature. It is finding the best compromise that makes the naval architect's task so interesting and rewarding, but also difficult.

Some of the most important decision on the general form of the ship must be taken early on. Thus, for a high speed ferry, the designer must investigate the relative merits of mono-hull and multi-hull forms and compare these with surface effect vehicles and hydrofoils, all of which have been used in the past. These days the designer has more freedom than in the past when designs were largely based on a successful design providing a similar service. The lack of prototypes led to a natural wariness of change. These days the computer, with advanced *computer-aided design* (CAD) systems, provides an ability to study alternatives in enough depth to give confidence in the final product. Features such as seakeeping and strength can be established with a high degree of confidence and what may be termed a virtual prototype can be produced. The prospective owner can be taken on a walk through of the new ship before it leaves the drawing board. Simulators can give a feel for the navigation of the ship in confined waters. However, these approaches can be expensive and a prudent designer still makes good use of data from an earlier successful design.

Costs

To be efficient a ship must be able to carry out its intended functions economically. Costs are always important. Unless those of a merchant ship are less than the revenue it can earn, the ship will be a liability. For warships, which do not 'earn' in the commercial sense the cost effectiveness of a design is harder to define let alone assess. In the end the warship designer can only inform the naval staff of the cheapest way to meet the requirement. It has then to be decided whether this amount of money can be allocated from the defence budget against the competing bids of other requirements. If not, then the requirement must be reduced till an acceptable balance is achieved between need and affordability. For any ship costs should be *through life* costs, not just build costs. Thus it might be better to use more mechanization to reduce crew size if the cost of mechanizing is less than the associated crew costs over the life of the ship. These are not easy balances to assess. Besides being paid the crew must be trained, they need space on

board and so on. Mechanization will bring with it initial and maintenance costs, with the need for maintainers offsetting in part other crew reductions.

Assuming the ship can earn revenue this can be assessed for the years ahead using the anticipated freight rates. Build costs will arise early on and then operating costs, including costs of crew, bunkering, port charges, refitting and repair, will be spread over the life cycle. At the end of the day the owner hopes there will be a profit. Depreciation must be allowed for although it is not an item of cash flow.

All the cash flow elements must be brought to a common basis by treating them as though they occurred simultaneously. This is because cash has a time value in that it might be used more profitably in some other way. It is usual to apply *discounted cash flow* methods to establish a *net present value* for the comparison of different design options. A compound interest rate is used to determine the 'present' value of money to be spent in later years. The net present value must be positive if it is to be acceptable. The higher it is for any option the better that option is from an economic point of view. The process can be inverted to give the freight rate needed to give a net present value of zero.

DEVELOPING THE DESIGN

Design development is not a smooth 'one-way' progression. As a simple example, the power required of the main propulsion system cannot be finally decided until the shape and displacement of the ship are known, but these depend upon the size and weight of that propulsion system. The development of the design must be an iterative process. Intelligent guesses, often based on a previous design, known as the *type ship*, are needed in the early stages to ensure the first solutions are not too wide of the mark.

The type ship is one which is carrying out most of the functions asked of the new ship and which is judged to be close to the size needed. From this base the designer can get a first approximation to the principal dimensions of the new ship. Allowance would be made for different capacities, perhaps higher speed, a smaller crew and so on. A feel for the size of the ship will be obtained from the weight or volume of cargo to be carried. The type ship will then give a guide to the ratio of the dimensions but these can be modified to give the form coefficients desired to give the desired propulsive efficiency, seakeeping and manoeuvring characteristics. The values of ratios such as length to beam or draught must be checked as being within the usually accepted limits. Absolute dimensions must be compared with limiting values for ports and waterways the ship is to use.

From the principal dimensions first assessments of draughts, stability, power, etc. can be made. Each of these will lead to a better picture of the design. It is an iterative process which has been likened to a spiral because each ship feature must be considered more than once and at the end of each cycle the designer should have approached the final design more closely. However, the use of the term spiral implies a steady progression which ignores the step functions that occur such as when a larger machinery set has to be fitted or an extra bulkhead added, or some significant design change is deliberately introduced to meet some new regulation. A better analogy is a network which shows the many inter-dependencies present in the design. This network would really be a combination of a large number of inter-active loops.

Not all design features will be considered during every cycle of the design process. Initial stability would be considered early on, large angle stability would follow later but damaged stability would not be dealt with until the internal layout of the design was better defined. The first estimate of power, and hence machinery required, would be likely to be changed. There would be corresponding changes in structural weight and so the design develops. Some of the initial assessments, for instance that of the longitudinal bending moment, can be made by using approximate formulae. When the design is reasonably defined more advanced computer programs can be employed.

THE DESIGN PROCESS

There are a number of recognized stages in developing a new design. Different authorities use different terms for the various design stages. For the present purposes the terms *feasibility studies*, *contract design* and *full design* will be used. In talking of documentation it should be appreciated that much of the information is nowadays in electronic form, emanating from the CAD and feeding into computerized manufacturing systems.

Feasibility studies

The aim at the feasibility stage is to confirm that a design to meet the requirements is possible with the existing technology and to a size and cost likely to be acceptable to the owner. As explained above the starting point is usually a *type ship*. Several design options will be produced showing the trade-offs between various conflicting requirements or to highlight features that are unduly costly to achieve and may not be vital to the function of the ship. The options may be simply variations on a basic design theme, or they may involve radically different ways of meeting the requirements.

Contract design

Once the owner has agreed to the general size and character of the ship more detailed designing can go on. The *contract design*, as its name implies, is produced to a level that it can be used to order the ship from a shipbuilder, and a contract price quoted. By this stage all major features of the ship will have been determined. Usually some model testing will have been carried out to confirm the main performance parameters. Layout drawings will have been produced to confirm spaces allocated to various functions are adequate. The power and type of machinery will have been decided and the electrical power, chilled water, air conditioning, hydraulic and compressed air system capacities defined. The basic ship design drawings will be supported by a mass of supporting specifications which will control the development of the final design.

Full design

The detailing of the design can now proceed, leading to the drawings, or with computerized production systems, computer tapes, which are needed by the production department to build the ship. Included in this documentation will be the detailed specification of tests to be carried out including an inclining experiment to check stability and the sea trials needed to show that the ship meets the conditions of contract and the owner's requirements. These are not necessarily the same. For instance, for warships *contractor's sea trials* are carried out to establish that the contract has been met. Then, after acceptance, the Ministry of Defence carries out further trials on weapon and ship performance in typical seagoing conditions.

Also specified will be the shipyard tests needed to be carried out as fabrication proceeds. Thus the testing of structure to ensure watertight and structural integrity will be defined. Tests of pipe systems will lay down the test fluid and the pressures to be used, the time they are to be held and any permissible leakage.

Then there is the mass of documentation produced to define the ship for the user and maintainers. There are lists of spares and many handbooks. Much of this data is carried on the ship in microform, or electronically, to facilitate usage and to save weight and space.

Analysis of a design

As seen above, the requirements for the ship will lead to a range of equipments and systems to provide the capabilities demanded. Everything in the ship must serve a purpose, possibly several. The designer can produce diagrams showing how the various elements of a design interact to give it a specific capability. These are known as *dependency*

diagrams. Thus to meet the mobility capability the ship may need, inter alia:

- a set of main machinery, say a diesel engine;
- a gear box;
- a shaft with shaft bearings, stern tube and shaft bracket;
- a propeller.

These major elements will entail supporting equipments/systems such as:

- lubrication system;
- structural supports;
- electrical supplies;
- air supply and exhaust.

The diagram will show how all these elements are linked and how failure of any one element would affect the overall speed capability. Thus in a single screw ship the loss of the shaft will remove the mobility capability completely. In a multi-shaft ship the loss of one shaft only degrades the capability, and the degree of degradation can be assessed. The probability of loss, or degradation, of a capability can be calculated from the probabilities of failure of the individual components and how they interact with each other.

It must be remembered that *To Float* is one capability the ship must possess reflecting the facts that it must float at a reasonable draught and be stable. The external hull and internal watertight structure will contribute to this capability.

The dependency diagram can be a powerful design tool. Apart from availability which has already been touched upon they:

- Show how the design is configured to meet the requirements.
- Provide one way of breaking a design down into its constituent parts – systems, sub-systems and equipments.
- Enable costs to be allocated to capabilities so that the owner knows what each costs.
- Provide a framework for the tests and trials that will be needed to establish that the requirements have been met.

In using the diagrams in these ways it is important that the interfaces are clearly defined to ensure nothing is omitted or duplicated. Rules are needed on how those elements supporting more than one capability are to be dealt with. Going on one step they provide a vehicle for defining packages of responsibility that can be delegated to individuals

in the design and construction teams. That is, they provide a useful management tool.

Availability

An owner wants a vessel to be available for use when needed. This is not necessarily all the time. Many ships have a quiet season when time can be found for refitting without risk to the planned schedules. Ferries are often refitted in winter months for that reason. *Availability* is a function of *reliability and maintainability*.

Reliability can be defined as the probability of an artefact performing adequately for the time intended under the operating conditions encountered. This implies that components must have a certain *mean time between failure* (MTBF). If the MTBF is too low for a given component that component will need to be duplicated so that its failure does not jeopardize the overall operation.

Maintenance is preferably planned. That is, items are refurbished or replaced before they fail. By carrying out *planned maintenance* in quiet periods the availability of the ship is unaffected. The MTBF data can be used to decide when action is needed. To plan the maintenance requires knowledge of the *mean time to repair* (MTR) of components. Both MTBF and MTR data are assessed from experience with the components, or similar, in service. The other type of maintenance is *break-down maintenance* which is needed when an item fails in service. Unless the item is duplicated the system of which it is a part is out of action until repair is carried out.

The time taken to maintain can be reduced by adopting a policy of *refit or repair by replacement* (RBR). Under this scheme complete units or sub-units are replaced rather than being repaired in situ. Frigates with gas turbine propulsion are designed so that the gas turbines can be replaced as units, withdrawal being usually through the uptakes or downtakes. The used or defective item can then be repaired as convenient without affecting the ship's availability and the repairs can be carried out under better conditions, often at the manufacturer's plant. The disadvantage is that stocks of components and units must be readily available at short notice. To carry such stocks can be quite costly. But then an idle ship is a costly item. It is a matter of striking the right balance between conflicting factors. To help in making these decisions the technique of *availability modelling* can be used.

The dependency diagrams are used in availability modelling of the various ship capabilities. Some components of the diagram will be in series and others in parallel. Take the ability to move. The main elements were outlined above and the supporting functions such as lubricating oil pumps and machinery seatings as well the need for electrical

supplies and fuel. Large items such as the main machinery can be broken down into their constituent components. For each item the MTBF can be assessed together with the probability of a failure in a given time span. These individual figures can be combined to give the overall reliability of a system using an approach similar to the way the total resistance of an electric circuit is calculated from the individual resistances of items in series or parallel. High reliability of components is needed when many are used in a system. Ten components, each with a reliability of 99 per cent, when placed in series lead to an overall reliability of $(0.99)^{10} = 0.905$. Ten units in parallel would have a reliability of $(1 - (0.1)^{10})$, effectively 100 per cent.

Such analyses can highlight weaknesses which the designer can alleviate by fitting more reliable components or by duplicating the unit. They also provide guidance on which spares should be stocked and in what quantities, that is the *range and scale* of spares.

The impact of technology and computers

Over the last half-century technology has had a tremendous impact upon how ships are designed, built, operated and maintained. One could mention a myriad of examples but the following will serve as illustrations:

- (1) Satellites in space have made it possible for ships to locate their position to within a few tens of metres using *global positioning systems*. The satellites can also pick up distress signals and locate the casualty for rescue organizations. They can measure sea conditions over wide areas and facilitate the routing of ships to avoid the worst storms.
- (2) Materials technology. Modern materials require much less maintenance, reducing operating costs and manpower demands. *Reinforced plastics* can be used for local structures, superstructures and for the main hull. Such plastics can be configured to enable them to meet the local stresses efficiently. For example, carbon fibres can be aligned with the main stress direction. New hull treatments permit much longer intervals between dockings leading to higher ship usage rates and reduced costs of ownership. They also contribute to the battle against pollution of the sea environment.
- (3) Modern equipments are generally much more reliable with increased mean times between failures. Modularization and repair by replacement policies reduce downtime and the number of repair staff needed on board.

- (4) Electronically controlled operating and surveillance systems enable fewer operators to cope with large main propulsion systems and a wide range of ship's services.

The biggest impact has been the influence of the computer. Indeed, computers have made a vital contribution to many of the changes referred to above. But it is in the sequence of design, build, maintaining and running of ships that their influence has been greatest for the naval architect. In some cases these processes have changed almost beyond recognition although the underlying principles and objectives remain the same. As examples:

In design

- (1) CAD systems enable preliminary designs (PD), in response to a client's wishes, to be produced more rapidly, in greater detail and with greater accuracy than ever before. Large databases of type ships can be called upon. If the design is novel specialist software is usually available to assess all the major characteristics.
- (2) Once the customer has agreed the PD the computer already holds the basic definition with which to start the contract design phase. The hull form, machinery requirements, layouts and systems can be produced with all the data accurately integrated and recorded. Any changes in form can be reflected in compartment shapes, and the volumes recalculated, and so on. Changes in structure are reflected in weight, hydrostatic and stability up-dates. Computer-based directories of materials and equipment help in selecting equipments and fittings and integrating them into systems of known performance, cost and reliability.
- (3) Computer controlled draughting machines and virtual reality techniques can be used to inform the client about the design and provide a means for the customer, or classification society to make an input to the design development. Virtual reality can be used to show what the ship will look like from all angles, both internally and externally. These can be used instead of mock-ups or models to assist in achieving efficient layouts. A person can be taken for what is termed a 'walk through' of ship before the design leaves the drawing board.
- (4) The strength of CAD systems is that they are integrated suites of related programs. These can accommodate advanced programs for such things as structural strength evaluations, motion predictions and so on.

In production

- (1) Once the design is approved to build the data can be passed to the chosen shipyard in digital form. This reduces the risk of

misinterpretation of drawings and other data. Provided the designer's CAD and builder's *computer-aided manufacture* (CAM) systems are compatible it also reduces the builder's task in producing information for the production process.

- (2) The database is available to the builder to order material, equipment and fittings for the build process. The builder will develop the database as the design is developed to provide all the details for manufacture and, later, for passing on to those who have to maintain the equipments and systems.
- (3) In production the computer can deal with routine matters like stock control. It can control cutting and welding machines ensuring greater accuracy of fit, facilitating more extensive pre-fabrication and reducing built in stresses. It should lead to a better, more consistent, quality of product. Where more than one ship of a class is being built the ships will more closely resemble each other. This makes future modification easier to control.

In operation and maintenance

- (1) In the same way as the systems facilitated the passing of information from designer to builder, they make it easier to pass information on to those who are to operate and maintain the ship. Hydrostatic, hold and tank capacity, stability and strength data can be fed into the ship's own software systems to assist the captain in loading and operating the ship safely.
- (2) Listings of equipment and fittings, with code numbers, will ensure that any replacements and spares will meet the *form, fit and function* requirements. One advantage of the computer is the potential to reduce the amount of paper. Where hard copy is required some form of microfiche can be used, again reducing the stowage volume and weight.
- (3) Data can be provided on the layout of systems and how the designer intended they should be operated. Computer controlled displays, fed with information from a whole range of remote sensors, assist those who are responsible for decisions. Sensors can give early warning of incipient failures.
- (4) Computer-based decision aiding systems can be installed. For example, the master can be prompted on the loading sequences to eliminate the possibility of jeopardizing the stability or strength. In warships they can assist the captain when under enemy attack by suggesting the optimum actions to take in defending the ship. It needs to be emphasized that they are only used in an advisory capacity in these roles. They do not reduce the master's or captain's responsibility.

- (5) Computer-based simulators can assist in training navigators, machinery controllers and so on. These simulators can be produced to various levels of realism, depending upon the need. They may merely reproduce the display consoles and control levers, leaving the computer to calculate how the ship, or system, will respond to the input made. They can be mounted on a moving platform to reproduce the ship movements in response to control movements. Motions can be imposed representing the ship's response to waves to study the ability of an operator to remain vigilant under motion conditions. The computer can provide external stimuli, through goggles or screens, which the operator can expect in practice. For instance, a navigational simulator can provide pictures of a harbour and its approaches. Other ships can be added for extra realism.
- (6) All the on board tasks of management can benefit from the appropriate software.
- (7) The database provides a useful input to any surveyor. It shows what should be fitted and provides the 'hooks' upon which the results of successive surveys can hung. In this way the gradual deterioration of structure, say, can be logged, showing up potential trouble spots and helping decide when remedial action is needed.

The above brief description shows how all-pervading the computer has become. It must be remembered though that it is only a tool, albeit a very powerful one. As such it must, like all tools, be used intelligently by those who understand how to get the best out of it. It is an aid to the human, although artificial intelligence techniques can be used to provide great assistance to a relatively inexperienced person. So-called *expert systems* can store information on how a number of very experienced engineers would view a certain problem in a variety of circumstances. Thus a less experienced person (at least in that particular type of vessel or situation) can be guided into what might be termed good practice.

This is not to say that the tasks of the designer, builder or operator have been made easy. Some of the more humdrum activities have been removed such as tedious manual calculations of volumes and weights. But more knowledge is needed to carry out the total task. Whereas in the past a simple longitudinal strength calculation, using a standard wave, was all that was possible, a much more complex assessment is now usually demanded. That is if its cost can be justified. What waves should be taken as the design conditions for operation and for survival? How should the mesh be arranged in a finite element analysis? So the decisions pile up and the answers are not all easy ones. If they were the

naval architect would not be needed and the master could be replaced by the computer.

SOME GENERAL DESIGN ATTRIBUTES

It has been seen that a ship will need to possess certain characteristics, or attributes, to meet an owner's requirements. It is constructive to consider some general attributes of design which apply to all, or most, ship types. Different ship types are discussed in a later chapter.

Capacity and size

Usually there will be a certain volume of goods the ships of a fleet need to carry. This may have been established by a market survey. The 'goods' may be cargo, people or weaponry. How many ships are needed and the amount to be carried in each individual ship will depend upon the rate at which goods become available. This will depend in turn, upon the supporting transport systems on land. Taking ferries as an example, one super ferry sailing each day from Dover to Calais, capable of carrying one day's load of lorries, cars and passengers, would not be popular. Transit for most would be delayed, large holding areas would be needed at the ports and the ship would be idle for much of the time. Whilst such an extreme case is clearly undesirable it is not easy to establish an optimum balance between size of ship and frequency of service. Computer modelling, allowing for the variability of the data, is used to compare different options and establish parameters such as the expected average waiting time, percentage of ship capacity used, and so on.

Transiting the world's major waterways

There may be limits imposed on the size of a ship by external factors such as the geographical features, and facilities, of the ports and waterways to be used. Three waterways are of particular interest:

- (1) **The Suez Canal** (The Suez Canal Authority). Built to reduce the passage time between Europe and the East. Its length is 192 km and the average transit time is 14 hours.
- (2) **The Panama Canal** (The Panama Canal Commission). Connects the Atlantic and Pacific oceans.
- (3) **The St. Lawrence Seaway** (St. Lawrence Seaway Authority). Provides a link between the Great Lakes of North America and the Atlantic.

The use of each of these requires a ship to pay tolls and not to exceed certain critical dimensions. Both tolls and dimensions are subject to

detailed conditions and special certificates are needed. A designer/operator should consult the relevant authority for those details but a lot of data can be found on associated web sites. As regards dimensions a simplified table is given below (Table 2.1). These limitations have led to the terms *Suezmax* and *Panamax* being applied to bulk carriers just within the limits of dimension. Those not able to use the canals are referred to as *Capesize*.

Table 2.1 Examples of dimension limits for ships passing through waterways

	<i>Maximum length</i> (m)	<i>Maximum beam</i> (m)	<i>Maximum draught</i> (m)
Suez Canal	–	Depends on draught	19
Panama Canal	294.13	32.31	12.04
St. Lawrence Seaway	222.50	23.20	7.92

There is an air draught limit of 35.50 m in the St. Lawrence Seaway.

In the Suez Canal there are dredged channels which mean that greater draughts are permitted at certain beams and less draught for wider ships. There are plans to deepen the central channel.

Cargo handling

In deciding what cargo handling equipment to fit, a balance is needed between giving a ship the ability to load and discharge its own cargo and reliance upon the terminal port facilities. If the ship is to operate between well-defined ports the balance may be clear. If the ship is to operate more flexibly it may not be able to rely on specialist unloading equipment and have to carry more of its own.

The development of the container ship was closely linked to the development of special container ports and the supporting road and rail networks for moving the containers inland. Similarly large crude oil carriers can expect good facilities at the loading port and the refinery terminal.

Influence of nature of goods carried

Particularly for those goods where large volumes are to be shipped the nature of the cargo has come to dictate the main features of the ship. The wool clippers on the Australian run were an early example. More recently tankers have come to the fore and with the growing demand for oil and its by-products, the size of tanker grew rapidly. The major influences are the possible storage methods and the means of loading and discharging. Oil can be carried in large tanks and can be pumped

out. Some particulate cargoes can be handled similarly or by conveyor belts and huge grabs. This has led to bulk carriers for grain, iron ore and coal.

Mixed cargoes are often placed in containers of a range of standard sizes. This improves the security in transit and reduces time in port. In other cases the cargo is brought to the ship in the land transport system units. First came the train ferries and then the roll on/roll off ships. Cars can be driven on and off for delivery of new cars around the world or for people taking their cars on holiday.

Perishable goods have led to the refrigerated ships, the *reefers*. Bulk carriage of gas has been possible with a combination of refrigeration and pressurized tanks.

Speed

Speed can be an emotive issue. Some authorities regard high speed as a status symbol but it is expensive of power and fuel and if pitched too high can lead to an uneconomic ship. It is an important input to the analysis referred to above. Faster ships can make more journeys in a given time period. Passengers like short passage times and are often prepared to pay a premium to get them as in the case of high speed catamaran ferries. Some goods require to be moved relatively quickly. They may be perishable and a balance must be struck between refrigeration and a fast transit. For other products speed may be of little consequence. For instance, as long as enough oil is arriving in port each day it does not matter to the customer how long it has been on passage. It is important to the ship owner who needs to balance speed, size, number of ships and capital locked up in goods in transit to achieve the desired flow rate economically.

For high speed ships wavemaking resistance is a major factor and the design will have a finer form. At low speeds frictional resistance will dominate and fuller, bluffer, forms can be used with greater cargo carrying ability on a given length. When considering speed, allowance must be made for the average voyage conditions expected. Two ships capable of the same still water maximum speed may differ significantly in their ability to maintain speed in rough weather.

Seakeeping

In its broadest sense seakeeping embraces all aspects of a ship that enable it to put to sea and operate safely on the trade routes it is to ply. Whilst concerned with all these, the naval architect usually uses the term to cover the behaviour of the ship in response to waves, including:

- its motions – principally roll, pitch and heave;
- wetness;

- slamming;
- speed reduction, whether enforced or voluntary to reduce motions.

The naval architect will select a form judged to provide good seakeeping characteristics. Stabilization can be used to reduce roll if desirable.

Manoeuvrability

Manoeuvrability is not too important for a ship in the open ocean. In restricted waters it can be critical. Stopping distances of the huge super tankers are very large. Astern power must be adequate to give the desired deceleration. A balance must be struck between giving a ship very good manoeuvrability and relying upon tugs for assistance in port. What is meant by good manoeuvrability and means of providing it in a ship are discussed under Manoeuvring (Chapter 13). Twin shafts, azimuthing propellers and lateral thrust units are some of the means used to obtain good manoeuvrability. These cost money and the cost must be set against the cost and delays of using tugs, remembering a tug may not always be available when needed. Ferries which frequently berth and unberth will normally be designed to operate without the assistance of tugs except in exceptional weather conditions. For long haul ships providing a high degree of manoeuvrability could be uneconomic.

Floating oil drilling rigs require exceptionally good performance in maintaining their position relative to the ground and for that reason they are provided with dynamic positioning systems. A series of thrusters under computer control are constantly correcting the position against the effects of wind, current and waves. In such vessels fin stabilizers are of little use for reducing roll and some form of tank system would be fitted if needed. Mine countermeasure ships also need to be able to maintain an accurate path over the ground if a suspected minefield is to be swept with the minimum number of passes and in maximum safety.

SAFETY

People are increasingly aware of safety issues in their daily lives and they are unwilling to accept levels of risk that might have been acceptable 50 or 100 years ago. The *Titanic* disaster brought home the fact that no ship is unsinkable, no matter how big. The loss of life in the *Herald of Free Enterprise* and the *Estonia* highlighted the potential dangers of designs which had large open deck spaces for the convenience of loading, and off loading, cars. This showed the danger that changes in design, as technology develops, can get ahead of the regulations intended to promote safety.

Efforts by the international community are beginning to improve the situation but the naval architect must not become complacent about safety. Some incidents such as those involving large tankers going aground and polluting the local shoreline hit the headlines. The general public, however, is usually unaware of unexplained ship losses, too often involving large and relatively new ships. The *MV Derbyshire* was such a case until the relatives and unions lobbied the government. Subsequent investigations and research led, amongst other things to the finding of the hull on the sea bed, to the tightening up of regulations concerning hatch covers and the acceptance that freak waves are not as rare as previously thought. In bulk carriers water ingress alarms are being fitted and so are double side hulls. Some ships are provided with hull stress monitoring systems involving strain gauges, pressure transducers and motion sensors. These help the master avoid undue straining of the hull at sea and during loading and unloading.

In recent years bulk carriers, tankers and Ro-Ro ships have received quite a lot of attention from the maritime community. Whilst still more needs to be done in those areas they are not the only causes for concern. Spouge (2003) pointed out that of losses of ships over 100 gross tonnage in the period 1995–2000, 42 per cent were general cargo ships and 25 per cent fishing vessels. The high rate of cargo ship loss is due in part to the greater number of these ships in service but if the loss rate per 1000 ship years is taken, figures of about 5.4, 3.3 and 1.5 are obtained for cargo ships, dry bulk carriers and oil tankers respectively.

The lessons to be learnt are:

- (1) It is not just high profile ships that need the naval architect's attention. Cargo ships also accounted for 37 per cent of the fatalities in the cases of total ship loss over 100 gross tonnage.
- (2) It is essential to analyse the data available on losses to detect trends and potential reasons for the losses so that corrective action can be taken.

Many, if not most, of the ships lost will have been built, maintained and manned in accord with the latest rules and regulations. It is clear that a ship can be designed to meet all existing regulations and yet not be as safe as it could, and should, be. This is partly due to:

- (1) Regulations having to be agreed by many authorities. As such they are often a compromise between what is regarded by many as the best practice and what others feel to be unduly restrictive or are prepared to accept for economic reasons.
- (2) The time lag between failures being experienced, analysed, the corrective action decided upon, agreed and implemented.

- (3) Advancing technology and changing trade requirements leading to ships with new features, and operating patterns, which have not been fully proven. Testing of hydrodynamic or structural models, and of materials in representative conditions can help but the final proof of the soundness of a design is its performance at sea.

It must be accepted that ships cannot be made completely safe against all eventualities. Some measures to improve safety might:

- (1) Make it virtually unusable. For instance too great a level of internal watertight sub-division, carried up high in the ship, would make it very difficult to move around or to stow cargo effectively.
- (2) Be very costly, making the ship uneconomic to operate. It is this factor that makes many owners unwilling to do more than required. They fear competitors will do the minimum and get ships which are cheaper to own and operate. Fortunately some owners do recognize the need to do more than the legal minimum. They will benefit if their better safety record attracts ship-pers and passengers.

Damage scenarios

A ship can be seriously damaged by, or lost because of:

- (1) Water entering as a result of damage or human error in not having watertight boundaries sealed. This can lead to capsize or foundering.
- (2) Fire or explosion.
- (3) Structural failure due to overloading, fatigue or fracture, possibly brittle in nature. Failure may be of the overall hull girder or local, say in way of a hatch cover, so permitting the ingress of water.
- (4) Loss of propulsive power or steering, leading to collision or grounding.

Action by the designer

Apart from meeting all the legal requirements, a designer should:

- (1) Consider whether any novel features of a design require special consideration.
- (2) Look for any potentially weak spots which can be improved. This will often be at little cost if addressed early enough in the design process.

- (3) Use the dependency diagrams drawn up as part of the design process to establish where duplication of critical equipments would be beneficial.
- (4) Ensure the builder and operators are aware of the reasons the design is configured in the way it is, to ensure that this intent is carried through into the ship's service life.
- (5) Carry out *failure mode effect analyses* (FMEA) of critical equipments and systems. This calls for experience of failures and why they occur and requires a dialogue between the designer and users.
- (6) Produce a *safety case*, identifying how a ship might suffer damage, the probability of occurrence and the potential consequences.

Some specific aspects of safety, such as the dangers of grounding and the vulnerability of warships, are dealt with separately in various chapters.

The safety case

The safety case concept consists of four main elements:

- (1) The safety management system, including establishing, implementing and monitoring policies. It is these policies that set the safety standards to be achieved, that is, the aims. It is the opposite of the prescriptive approach in which the system is made to adhere to a set of rules and regulations. The safety case is targeted at a particular ship, or installation, in a given environment with a specified function.
- (2) Identification of all practical hazards.
- (3) Evaluating the risk level of each hazard and reducing the level of hazards for which the risk is judged to be unacceptable. The risk of a hazard is the product of its probability of occurrence and the consequences if it does occur. The judgement of acceptability is a difficult one. It is usually based on what is known as the ALARP (**As Low As Reasonably Possible**) principle.
- (4) Being prepared for emergencies that could occur.

Such studies can guide the designer as to the safety systems that should be fitted on board. Analysis might show a need for external support in some situations. For instance, escort tugs might be deemed desirable in confined waters or areas of special ecological significance. Many of the factors involved can be quantified, but not all, making good judgment an essential element in all such analyses. The important thing is that a process of logical thought is applied, exposed to debate and decisions monitored as the design develops. Some of the decisions will depend upon the master and crew taking certain actions

and that information should be declared so that the design intent is understood.

Safety is no academic exercise and formal assessments are particularly important for novel designs or conventional designs pushed beyond the limits of existing experience. Thus following the rapid growth in size of bulk carriers, that class of ship suffered significant numbers of casualties. One was the *MV Derbyshire*, a British OBO carrier of 192 000 tonne displacement. From 1990 to 1997, 99 bulk carriers were lost with the death of 654 people. An IMO conference in 1997 adopted important new regulations which it was hoped would help prevent loss of the ship following an accident. These came into force in 1999.

The loss of a ship for some unknown reason is most worrying. To assist with these, and in accident investigations more generally, a new regulation was adopted by IMO in 2000 which will require many ships to be fitted with 'black boxes' similar to aircraft practice of many years standing. These *voyage data recorders* (VDRs), to give them their correct title, are to be fitted in all passenger ships, and in other ships of 3000 gross tonnage upwards, constructed after July 2000. There is provision for retrospective fitting in some older ships.

The VDRs, whose use has previously been encouraged but not mandatory, will record pre-selected data relating to the functioning of the ship's equipment and to the command and control of the ship. It will be in a distinctive protected capsule with a location device to aid recovery after an accident.

Certain ships are also to be required to carry an *automatic identification system* (AIS) capable of providing data, such as identity, position, course and speed, about the ship automatically to other ships and shore authorities.

Vulnerability

A ship might be quite safe while it remains intact but be very likely to suffer extensive damage, or loss, as a result of a relatively minor incident. For instance, a ship with no internal sub-division could operate safely until water entered by some means. It would then sink. Such a design would be unduly *vulnerable*. This is why in the safety case the designer must consider all the ways in which the ship might suffer damage.

An incident may involve another ship, in collision say, or result from an equipment failure. Thus loss of the ability to steer the ship may result in its grounding. It can arise from human error, the crew failing to close and secure watertight doors and hatches. It will often be the result of several factors coming into play at the same time.

For each way in which a ship may be damaged, the outcome of that damage on the ship and its systems can be assessed. The aim is to highlight

any weaknesses in the design. Taking the steering system as an example, the various elements in the total system can be set out in a diagram showing the inter-relationships. There will be the bridge console on which rudder angles or course changes are ordered, the system by which these orders are transmitted to the pumps/motors driving the rudder and the rudder itself. If two rudders are fitted the two systems should be as independent as possible so that an incident causing one of the rudders to fail does not affect the other. If only one rudder is fitted the system would be less vulnerable if duplicate motors/pumps are provided. Wiring or piping systems and electrical supplies can be duplicated. Each duplication costs money, space and weight so it is important to assess the degree of risk and the consequences of failure. The consequences are likely to depend upon the particular situation in which the ship finds itself. Loss of steering is more serious close to a rocky coast than in the open ocean. It may be even more serious within the confines of a crowded harbour. Thus safety and vulnerability studies must be set within the context of likely operational scenarios.

It will be apparent to the student that probabilities play a major role in these studies and the statistics of past accidents are very valuable. For instance, from the data on the damaged length in collisions and groundings, the probability of the ship being struck at a particular point along its length and of a certain fraction of the ship's length being damaged in this way, what is likely to happen in some future incident, can be assessed. This is the basis of the latest IMO approach to merchant ship vulnerability. The probability of two events occurring together is obtained from the product of their individual probabilities. Thus the designer can combine the probabilities of a collision occurring (it is more likely in the English Channel than in the South Pacific), that the ship will be in a particular loading condition at the time, that the impact will occur at a particular position along the length and that a given length will be damaged. The crew's speed and competence in dealing with an incident are other factors. IMO have proposed standard shapes for the probability density functions for the position of damage, length of damage, permeability at the time and for the occurrence of an accident. There is a steady move towards probabilistic methods of safety and vulnerability assessment and passenger and cargo ships are now studied in this way.

It must be accepted, however, that no ship can be made absolutely safe under all possible conditions. Unusual combinations of circumstances can occur and freak conditions of wind and wave will arise from time to time. In 1973 the *Benchruachen*, with a gross tonnage of 12 000, suffered as a result of a freak wave. The whole bow section 120 feet forward of the break in forecastle was bent downwards at 7 degrees. When an accident does occur the question to be asked is whether the design

was a reasonable one in the light of all the circumstances applying. No matter how tragic the incident the design itself may have been sound. At the same time the naval architect must be prepared to learn as a result of experience and take advantage of developing technology. For instance knowledge of 'freak waves' is improving and oceanographers are providing the data and tools for assessing the probability of meeting extreme waves.

SUMMARY

The general approach to design and some specific design attributes have been discussed. The importance of safety has been emphasized. It is apparent that a naval architect needs a clear set of definitions within which to work and an ability to:

- Calculate areas and volumes of various shapes.
- Establish the drafts at which a ship will float and how its draughts will change with different loadings.
- Study the stability of a vessel both intact and after damage.
- Determine the powering needed to achieve the desired speed in service on the routes the ship is to ply.
- Understand the environment in which a ship operates and its responses to that environment.
- Ensure the ship is adequately strong.
- Provide the ship with adequate means for manoeuvring in confined waters or on the ocean.

All these areas of knowledge are addressed in the ensuing chapters. Then a number of ship types are discussed to show how the requirements of an operator can lead to significantly different ships although they obey the same fundamental laws.

3 Definition and regulation

DEFINITION

A ship's hull form helps determine most of its main attributes; its stability characteristics; its resistance and therefore the power needed for a given speed; its seaworthiness; its manoeuvrability and its load carrying capacity. It is important, therefore, that the hull shape should be defined with some precision and unambiguously. To achieve this the basic descriptors used must be defined. Not all authorities use the same definitions and it is important that the reader of a document checks upon the exact definitions applying. Those used in this chapter cover those used by Lloyd's Register and the United Kingdom Ministry of Defence. Most are internationally accepted. Standard units and notation are discussed in Appendix A.

The geometry

A ship's hull is three dimensional and, except in a very few cases, is symmetrical about a fore and aft plane. Throughout this book a symmetrical hull form is assumed. The hull shape is defined by its intersection with three sets of mutually orthogonal planes. The horizontal planes are known as *waterplanes* and the lines of intersection are known as *waterlines*. The planes parallel to the middle line plane cut the hull in *buttock (or bow and buttock) lines*, the middle line plane itself defining the *profile*. The intersections of the athwartships planes define the *transverse sections*.

Three different lengths are used to define the ship (Figure 3.1). The *length between perpendiculars* (lbp), the *Rule length* of Lloyd's Register, is the distance measured along the summer load waterplane (the design waterplane in the case of warships) from the after to the fore perpendicular. The *after perpendicular* is taken as the after side of the rudder post, where fitted, or the line passing through the centreline of the rudder pintles. The *fore perpendicular* is the vertical line through the intersection of the forward side of the stem with the summer load waterline.

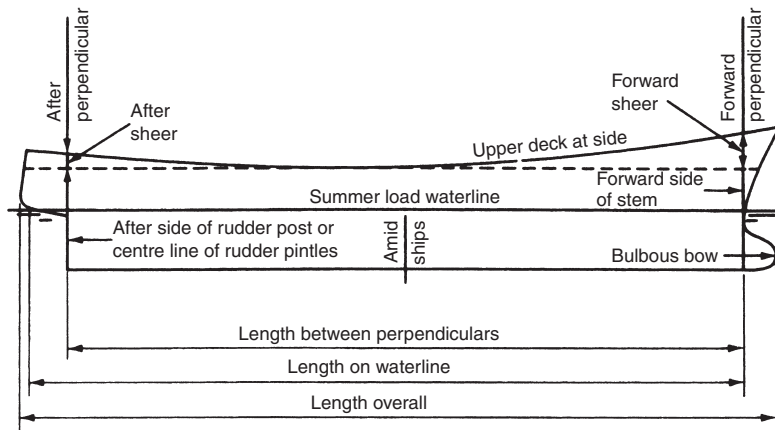


Figure 3.1 Principal dimensions

The *length overall* (loa) is the distance between the extreme points forward and aft measured parallel to the summer (or design) waterline. Forward the point may be on the raked stem or on a bulbous bow.

The *length on the waterline* (lwl) is the length on the waterline, at which the ship happens to be floating, between the intersections of the bow and after end with the waterline. If not otherwise stated the summer load (or design) waterline is to be understood.

The mid-point between the perpendiculars is called *amidships* or *midships*. The section of the ship at this point by a plane normal to both the summer waterplane and the centreline plane of the ship is called the *midship section*. It may not be the largest section of the ship. Unless otherwise defined the *beam* is usually quoted at amidships. The beam (Figure 3.2) most commonly quoted is the *moulded beam*, which is the greatest distance between the inside of plating on the two sides of the

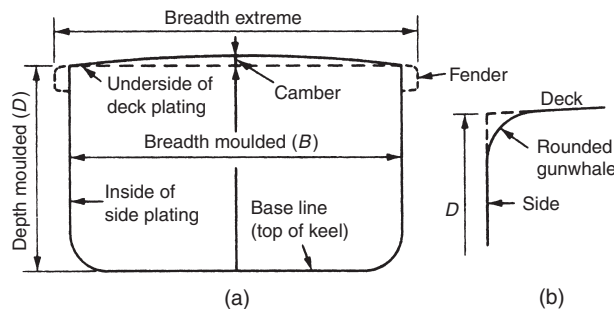


Figure 3.2 Breadth measurements

ship at the greatest width at the section chosen. The *breadth extreme* is measured to the outside of plating but will also take account of any overhangs or flare.

The ship *depth* (Figure 3.2) varies along the length but is usually quoted for amidships. As with breadth it is common to quote a *moulded depth*, which is from the underside of the deck plating at the ship's side to the top of the inner keel plate. Unless otherwise specified, the depth is to the uppermost continuous deck. Where a rounded gunwhale is fitted the convention used is indicated in Figure 3.2.

Sheer (Figure 3.1) is a measure of how much a deck rises towards the stem and stern. It is defined as the height of the deck at side above the deck at side amidships.

Camber or *round of beam* is defined as the rise of the deck in going from the side to the centre as shown in Figure 3.3. For ease of construction camber may be applied only to weather decks, and straight line camber often replaces the older parabolic curve.

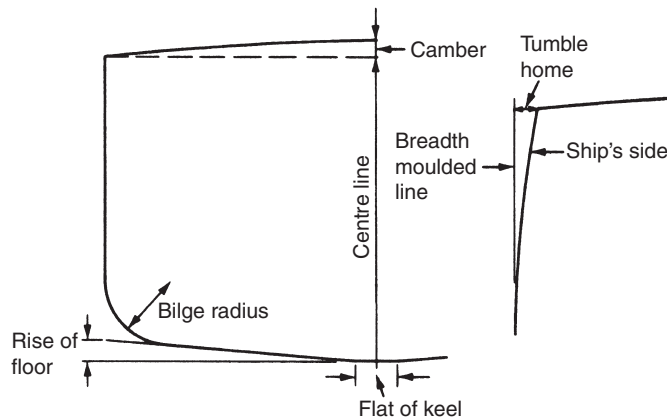


Figure 3.3 Section measurements

The bottom of a ship, in the midships region, is usually flat but not necessarily horizontal. If the line of bottom is extended out to intersect the moulded breadth line (Figure 3.3) the height of this intersection above the keel is called the *rise of floor* or *deadrise*. Many ships have a flat keel and the extent to which this extends athwartships is termed the *flat of keel* or *flat of bottom*.

In some ships the sides are not vertical at amidships. If the upper deck beam is less than that at the waterline it is said to have *tumble home*, the value being half the difference in beams. If the upper deck has a greater beam the ship is said to have *flare*. All ships have flare at a distance from amidships.

The *draught* of the ship at any point along its length is the distance from the keel to the waterline. If a *moulded draught* is quoted it is measured from the inside of the keel plating. For navigation purposes it is important to know the maximum draught. This will be taken to the bottom of any projection below keel such as a bulbous bow or sonar dome. If a waterline is not quoted the design waterline is usually intended. To aid the captain draught marks are placed near the bow and stern and remote reading devices for draught are often provided. The difference between the draughts forward and aft is referred to as the *trim*. Trim is said to be *by the bow* or *by the stern* depending upon whether the draught is greater forward or aft. Often draughts are quoted for the two perpendiculars. Being a flexible structure a ship will usually be slightly curved fore and aft. This curvature will vary with the loading. The ship is said to *hog* or *sag* when the curvature is concave down or up respectively. The amount of hog or sag is the difference between the actual draught amidships and the mean of the draughts at the fore and after perpendiculars.

Air draught is the vertical distance from the summer waterline to the highest point in the ship, usually the top of a mast. This dimension is important for ships that need to go under bridges in navigating rivers or entering port. In some cases the topmost section of the mast can be struck to enable the ship to pass.

Freeboard is the difference between the depth at side and the draught, that is it is the height of the deck above the waterline. The freeboard is usually greater at the bow and stern than at amidships. This helps create a drier ship in waves. Freeboard is important in determining stability at large angles.

Representing the hull form

The hull form is portrayed graphically by the *lines plan* or *sheer plan* (Figure 3.4). This shows the various curves of intersection between the hull and the three sets of orthogonal planes. Because the ship is symmetrical, by convention only one half is shown. The curves showing the intersections of the vertical fore and aft planes are grouped in the *sheer profile*; the waterlines are grouped in the *half breadth plan*; and the sections by transverse planes in the *body plan*. In merchant ships the transverse sections are numbered from aft to forward. In warships they are numbered from forward to aft although the forward half of the ship is still, by tradition, shown on the right hand side of the body plan. The distances of the various intersection points from the middle line plane are called *offsets*.

Clearly the three sets of curves making up the lines plan are interrelated as they represent the same three dimensional body. This interdependency

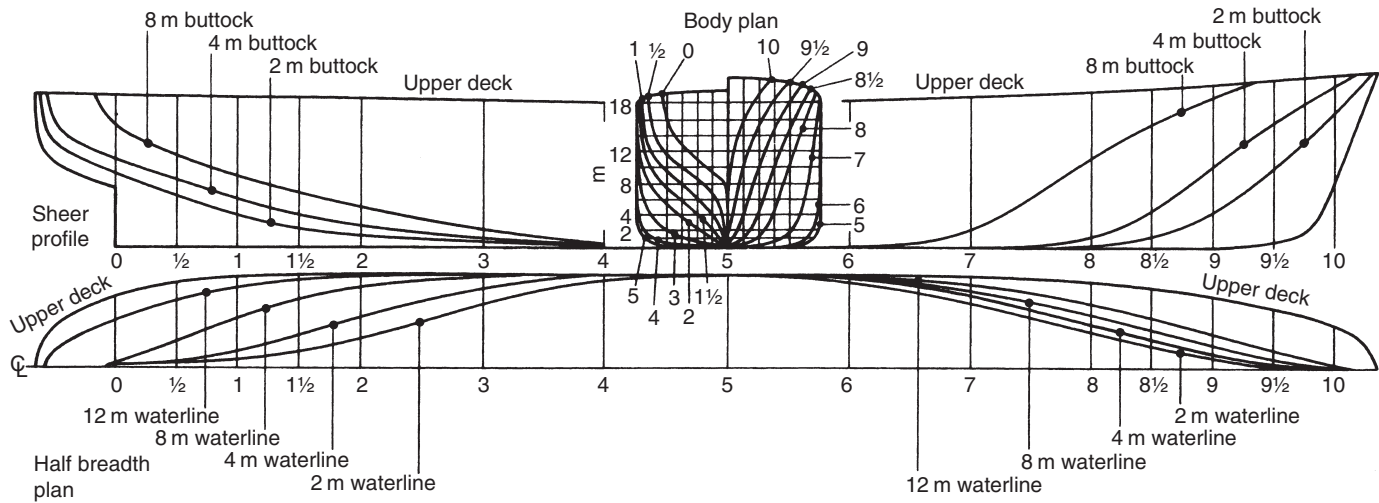


Figure 3.4 Lines plan

is used in manual fairing of the hull form, each set being faired in turn and the changes in the other two noted. At the end of the iteration the three sets will be mutually compatible. Fairing is usually now carried out by computer. Indeed the form itself is often generated directly from the early design processes in the computer. Manual fairing is done first in the design office on a reduced scale drawing. To aid production the lines used to be laid off, and refaired, full scale on the floor of a building known as the mould loft. Many shipyards now use a reduced scale, say one-tenth, for use in the building process. For computer designed ships the computer may produce the set of offsets for setting out in the shipyard or, more likely, it will provide computer tapes to be used in computer aided manufacturing processes.

In some ships, particularly carriers of bulk cargo, the transverse cross section is constant for some fore and aft distance near amidships. This portion is known as the *parallel middle body*.

Where there are excrescences from the main hull, such as shaft bossings or a sonar dome, these are treated as *appendages* and faired separately.

Hull characteristics

Having defined the hull form it is possible to derive a number of characteristics which have significance in determining the general performance of the ship. As a floating body, a ship in equilibrium will displace its own weight of water. This is explained in more detail later. Thus the volume of the hull below the design load waterline must represent a weight of water equal to the weight of the ship at its designed load. This *displacement*, as it is called, can be defined as:

$$\Delta = \rho g \nabla$$

where:

ρ = the density of the water in which the ship is floating

g = the acceleration due to gravity

∇ = the underwater volume.

It should be noted that displacement is a force and will be measured in newtons.

For flotation, stability, and hydrodynamic performance generally, it is this displacement, expressed either as a volume or a force, that is of interest. For rule purposes Lloyd's Register also use a *moulded displacement* which is the displacement within the moulded lines of the ship between perpendiculars.

It is useful to have a feel for the fineness of the hull form. This is provided by a number of *form coefficients* or *coefficients of fineness*. These are defined as follows, where ∇ is the volume of displacement:

$$\text{Block coefficient } C_B = \frac{\nabla}{L_{PP} BT}$$

where:

L_{PP} is length between perpendiculars

B is the extreme breadth underwater

T is the mean draught.

Corresponding to their moulded displacement Lloyd's Register use a block coefficient based on the moulded displacement and the Rule length. This will not be used in this book.

$$\text{Coefficient of fineness of waterplane, } C_{WP} = \frac{A_W}{L_{WL} B}$$

where:

A_W is waterplane area

L_{WL} is the waterline length

B is the extreme breadth of the waterline.

$$\text{Midship section coefficient, } C_M = \frac{A_M}{BT}$$

where:

A_M is the midship section area

B is the extreme underwater breadth amidships.

$$\text{Longitudinal prismatic coefficient, } C_p = \frac{\nabla}{A_M L_{PP}}$$

It will be noted that $C_M \times C_p = C_B$

$$\text{Vertical prismatic coefficient, } C_{VP} = \frac{\nabla}{A_W T}$$

It will be noted that these are ratios of the volume of displacement to various circumscribing rectangular or prismatic blocks, or of an area to the circumscribing rectangle. In the above, use has been made of displacement and not the moulded dimensions. This is because the coefficients are used in the early design stages and the displacement