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

Hydrodynamics and Ship Performance

J. A. H. Paffett

Phil. Trans. R. Soc. Lond. A 1972 **273**, 77-84
doi: 10.1098/rsta.1972.0083

Phil. Trans. R. Soc. Lond. A. **273**, 77–84 (1972) [77]
Printed in Great Britain

Hydrodynamics and ship performance

By J. A. H. Paffett
National Physical Laboratory Ship Division, Feltham, Middlesex

Developments are discussed under the headings size, speed, seakeeping and ship handling. There is a note on trends in ship hydrodynamics research.

Size limits are likely to be set by geography rather than technology; million tonne ships are possible but seem unlikely.

Speed in displacement ships is unavoidably expensive; high speeds are possible with hydrofoils and hovercraft but costs are likely to limit their use.

In seakeeping means of roll damping will be improved, as will the ability to sustain service speeds in adverse weather.

Considerable improvements are probable in the handling qualities of ships, with gains in safety and port efficiency.

1. Introduction

Ship hydrodynamics is the study of what happens where the ship's hull meets the water. Markets, industries and politics are man-made influences which will have changed by the 1980s, doubtless with visible effects upon the inboard and upper parts of ships. Ocean wave spectra, chart soundings and the physical properties of water are, on the other hand, fixed quantities; the hydrodynamicist is fortunate in that his principal constraints are set not by legislators but by nature, which is more predictable, and so the wet part of the hull will not be so very different in the eighties from the hulls we have known in the sixties and seventies. In discussing hydrodynamics therefore we shall be looking at changes which may well be important but which are unlikely to be spectacular.

2. The size of ships

The most obvious development in merchant ships over the past ten years has been the remarkable increase in size, a phenomenon with some claim to being spectacular which has continued in spite of repeated assertions that the largest possible size has been reached. Size has brought economies, and the curve of cost per unit cargo mass per unit distance has fallen continuously as size has gone up. Will the process go up to a million tonnes and beyond? Recent studies have established the engineering feasibility of half-million and one-million tonne tankers, and at least two U.K. shipyards are prepared to build in this size range. Hydrodynamically there would be no obstacles.

Owners are, however, showing some disinclination to break or even approach the 'megatonne barrier'. The curve of cost against size has begun to flatten out; moreover, around 300000 tonnes it becomes necessary to use two or even three propellers instead of one with consequent multiplication of shafting and machinery, and this puts an upward kink in the curve. The increased liability to wave-induced vibration (referred to below) and the limitation on tank sizes proposed by I.M.C.O. also make the large ship less attractive. Insurance costs rise too with size, and figures have been published showing premiums to be the major part of running costs in the largest ships, outweighing fuel and crew costs. We must also consider the remainder of the system of which the tanker is part; shore installations and refineries can digest deliveries in quarter-million tonne loads, but million-tonne deliveries may well call for expenditure ashore on storage tanks, pipes and berths.

Water depths

But most important of all, we are running out of seawater. Present major tankers drawing 20 m loaded can barely scrape into Rotterdam and a few other ports; they have to offload part of their cargo at sea before slithering into Fawley. One million-tonne design recently studied had a load draught of 30 m, enough to condemn it to loading and unloading out at sea. Even if routes and terminals can be chosen to accommodate such ships, operation at large draughts bring hazards, some obvious, some less so. It is not enough that charted sea-depth exceed the nominal draught; account must also be taken of meteorological 'surges' which cause the tide to differ from predicted values, and of hydrodynamic effects which cause a ship moving in shallow water to 'squat' or increase its draught, and which degrade the steering performance. Moreover, while available charts are reasonably accurate down to 10 m or so, they are far less reliable at 30 m. A really major hydrographic charting operation will be required across large areas of ocean in the 20–30 m depth range before these waters can be fully and safely exploited by loaded tankers. If owners want to operate megatonne tankers in the eighties, they will have to see that hydrographic operations are greatly extended in the seventies.

To increase capacity without at the same time increasing draught, wide shallow designs can be adopted, but there is a drag penalty which will push the cost curve up again. Some development in the direction of the relatively short, wide, shallow ship seems likely. Such forms, in combination with extensive dredging, surveying and the use of offshore moorings could undoubtedly make million tonne tankers possible in the eighties; but on balance it seems unlikely that there will be many – if any.

3. SPEED

The recent size growth of bulk carriers and tankers has not been accompanied by a corresponding rise in speed. The largest of these ships still operate at around 16 knots (8 m/s), a figure little changed over the years.

It is worth looking at this question of speed more closely. If we build a series of geometrically similar hulls and drive them at equal Froude numbers – i.e. at speeds proportional to the square roots of the lengths – we shall find the resistance force per unit weight of the ship nearly the same in each case. Since for similar designs cargo weight is nearly a fixed fraction of ship weight, we can show that the energy to propel a given weight of cargo a given distance is the same in each ship.

Ship weight is proportional to the cube of the length. It follows that speed will go up roughly as the sixth root of the cargo weight for constant fuel cost. However, the actual rate of speed increase has been considerably less than this. This grossly simplified explanation accounts for some of the economy of size.

Speed at sea is in fact a very expensive commodity. At low speeds the power to drive a given ship goes up as the cube of the speed; as wavemaking becomes important the index climbs until the engine power is rising as the seventh power of the speed. Beyond the hump in the resistance curve hydrodynamic lift forces become important, the ship begins to plane and the index falls again as the wave pattern fades away. Hovercraft, hydrofoils and planing boats operate in this elusive region beyond the resistance hump; but even in the 1980s displacement craft carrying more than a hundred tonnes or so of cargo are unlikely to climb beyond the foothills. The barriers are not only the enormous mechanical power required, but the noise, violent motions, the disturbance caused ashore by the wave pattern and so on. If one wants to travel really fast, one has to pay a high price to do it at the air–sea interface.

Conversely, of course, travelling slowly afloat is almost ludicrously cheap. Buoyancy is a supporting force which demands zero power, which is precisely calculable and evenly distributed. It made the industrial revolution in this country possible by enabling large masses of materials to be moved along the canals by the moderate horse power then available. The railways later gained an advantage by offering a near constant frictional force in lieu of the speed-squared friction of the canal boats; but when we come to kilotonne and megatonne cargo loads buoyancy becomes attractive again. The ship, in the eighties and beyond, will remain the cheapest way of moving large masses through long distances; and the canal barge may well deserve another look for inland and intra-European bulk transport, as a more socially acceptable alternative to the thundering monster lorry.

(*a*) *Fast craft*

For ferries perhaps and military purposes we may need to operate beyond the hump. In planing craft the shock accelerations in the open sea can be large and destructive, but sophisticated control engineering can produce hydrofoil craft which cut with a steady glide through rough seas, and hovercraft can cushion themselves from the waves to some extent with a resilient pocket of air. Undoubtedly both types can and will be developed for specialized services in larger sizes into the eighties. In both of these types the designer is hard put to it to leave a useful payload margin between lift and self-weight, and is driven to using expensive aircraft-type structures and lightweight machinery. In hydrofoils, scaling up beyond a few hundred tonnes all-up mass is made difficult by the onset of foil cavitation and the severe structural problem set by the need to concentrate the entire gravity and acceleration loads on to the thin flat foil members. In hovercraft the support forces are more comfortably cushioned; all-up masses running into some thousands of tonnes can probably be achieved, but the main problem will be set by the need to generate propulsive forces. Air propulsion becomes increasingly inefficient and noisy with size, so the largest hovercraft will need to use some form of water propulsion, thus losing their amphibious capability. It seems likely that even in the eighties economics are likely to confine non-displacement craft to specialized or high-intensity services where the cost can be borne.

(*b*) *Resistance reduction*

In the conventional speed range, there may still be some modest but useful gains to be made by developing hull forms of reduced drag. Ship resistance is a complex phenomenon and the relation between shape and drag is even yet not completely understood. Oddly enough, the forms offering most scope for improvement may be the very slow, bluff ones in use for tankers; development of boundary layer control methods may enable the very significant flow-separation component of drag to be cut usefully.

There are indications that unconventional shapes can be adapted with only small drag penalties; for instance, it may pay to adopt a hull formed from cheaply-fabricated shapes such as flats and cylinders if the reduction in first cost can be made to offset the resistance increase. There is scope here for a dialogue between hydrodynamicist and builder.

Unconventional expedients are sometimes advocated in the search for reduced resistance.

For a given all-up mass and speed, a catamaran or trimaran hull can sometimes be devised to have somewhat less resistance than the corresponding single hull; but the advantage is confined to a narrow range of speeds, and is most unlikely to offset the great increase in hull mass required to maintain strength in the multi-hull. The catamaran layout may be adopted in the eighties for special reasons – notably, its large deck-area and stability – but hardly for hydrodynamic reasons.

The submarine too is periodically put forward as the tanker of the future, on the grounds that a submerged vessel has no wave-making resistance. This is true, but it can be shown that the advantage only applies if the submarine is very large, very fast and well submerged. A 100000 tonne nuclear submarine to do 40 knots (20 m/s) could probably be built and operated outside the Continental shelf, but it seems unlikely that such a vessel would ever be allowed to enter the Channel or European waters submerged. On the surface she would have a much inferior performance to conventional ships of equal capacity. If cargo submarines are ever built it will be for operational reasons – such as penetrating the polar ice-cap – and not for hydrodynamic advantages.

(*c*) *Propulsion*

A free vehicle needs thrust to propel it at any speed. This can only be generated by changing the momentum of the circumambient fluid. As a device for doing this in large displacement ships no rival to the stern-mounted propeller is in sight. The designer of the eighties is not likely to achieve a very marked increase in present propeller efficiencies, although increased use of controllable-pitch propellers will improve the matching between engine and propeller. Other features of propulsion are amenable to improvement, notably vibration, much of which is propeller-induced. Such vibration damages cargoes, fatigues structures and upsets crews; it has become increasingly troublesome with the trend towards higher shaft powers in container ships and fuller bodies in tankers. Until recently, designers tended to choose hull form for minimum resistance and propeller parameters for maximum propulsive efficiency; by the eighties it is likely that they will be designing propeller–hull–rudder combinations as truly matched systems. It is possible that such systems may become more complex, incorporating ducts, sophisticated rudders, transverse thrusting and stabilizing devices. We may even see specialized firms with the appropriate know-how and machining capacity designing and supplying completely integrated stern systems to ship assembly plants. (One might note that there seems to be scope for specialist suppliers of other major ship components; for instance, completely fitted-out navigating bridges.)

Increasing speeds and thrusts lead eventually to cavitation, a phenomenon forced on the propeller designer by the physical properties of water, which insists upon boiling if propeller suction reduces its pressure to near zero. Above about 40 knots (20 m/s) he can either accept the inevitable and arrange for his propeller to operate with a constant and fully developed vacuous or ventilated cavity on the back of the blade; or he can scoop his water inboard and feed it through a pump to a sternwards jet. Water jet propulsion is relatively inefficient but can become attractive in fast craft where conventional propellers would cavitate; it also offers secondary advantages such as reduced vulnerability and adjustable thrust direction. So jets may well be seen propelling the fast ferries and patrol craft of the eighties. It is worth noting, however, that the cost of high speed is in this way aggravated; not only do we need high powers, but we are driven to less efficient, heavier and more complex propulsive devices in the form of pumps, ducting and inboard water.

4. SEAKEEPING

A ship is a solid body with six degrees of freedom, operating at the air-sea interface. The interface oscillates in time and extension; the ship is coupled to it through various stiffnesses in all six modes, one of the inescapable facts of physics which makes things difficult for sailors and naval architects, and helps passenger airlines.

Ship motion causes discomfort and injury to people, damage to cargo, fatigue stressing in structure, loss of speed and shipping of water. The ideal ship would have zero motion in all modes other than full speed ahead. Complete 'stabilization' would in theory be possible if we had an agent capable of generating controlled forces large enough to cancel out those of the sea, and a structure capable of withstanding them. However, the power of the sea to roll and pitch a ship dwarfs anything man can generate with his fins, tanks and gyroscopes, and it seems likely that true stabilization of large ships will still be out of reach in the eighties, and possibly in the nineties too. For hydrofoil craft the prospects are better. In light to moderate seas total stabilization can probably be approached in a hydrofoil with immersed foils and a sophisticated means of continuously adjusting foil lift.

(*a*) *Damping*

Although we cannot hope to keep large ships rock steady, some improvement is possible. One particular mode of motion is at once the most troublesome and the most amenable to treatment, namely roll. From the very nature of ships' hulls, they are lightly damped in roll and they commonly have natural roll periods in the range 10 to 15 s; unfortunately ocean wave spectra have much of their energy in the same range. Nature thus condemns us to risk resonance much of the time at sea. Fortunately a little damping goes a long way in resonant conditions, and we can use devices such as bilge fins to generate moments in the damping phase which will reduce roll amplitudes to half or less. Roll damping systems, often mis-named 'stabilizers', have existed for years; there is still scope for improvement in their performance. In particular it is likely that we shall see integrated systems for controlling motion in roll and yaw together. Unfortunately, the prospects for usefully damping pitching motion are much less bright.

(*b*) *Wetness and speed loss*

Ship motion, particularly pitching, commonly throws up water; sometimes this comes inboard and the ship is said to be 'wet'. Design to avoid wetness is largely a matter of experience, and there is still room for developing bow shapes which will combine dryness with satisfactory cargo-working layouts on deck. This is particularly important in container ships and fishing vessels.

Loss of speed due to rough seas can be involuntary – caused by the increase in drag – or voluntary, as when the captain deliberately reduces speed to avoid shipping water, or damage to ship or cargo. In either event, delay can be expensive, particularly in scheduled liner services. In large modern ships there is usually enough margin of power in hand to overcome the drag increment, but voluntary slowing is common enough; sometimes it is delayed too long, resulting in plating damage or loss of deck cargo. Improved hydrodynamic and structural design will doubtless enable us to maintain higher speeds in the eighties than now, notably by deferring or preventing 'slamming', the damaging concussion which occurs when a ship's bow rises clear out of the sea and plunges back into the water. However, nature will always be able to stage an occasional storm which will check man's best efforts in naval architecture.

(c) *Wave induced vibration*

A curious instance of the action of waves upon ships is provided by wave-induced hull vibration. A ship's hull is flexible and can be persuaded to vibrate in many modes, much as any freely-suspended beam. The effect of increasing a ship's size is to bring down the natural frequencies of vibration. Ships are now becoming so large that the frequencies of the simplest mode of vibration, the 'two-mode vertical', are falling well below 1 Hz. The ocean wave spectra encountered by the ship's bow can have appreciable energies at such frequencies; consequently the ship can be set into prolonged and troublesome oscillation by the waves. The only treatment at present available is to change course or speed, which costs money. The mass and stiffness of the system are virtually fixed; use of high tensile steel in the hull only lowers the natural frequencies and makes things worse. If a design cure is to be found before the eighties it seems likely that it will take the form of artificial damping built into the hull.

5. Ship handling

As well as steaming ahead in the open sea, every ship on occasion needs to start, stop and steer in confined waters. Ship handling in this context refers to the ability of a ship to manoeuvre accurately and safely in restricted or crowded waters; it depends upon the Master's skill and upon the ship design. Handling is becoming increasingly important because of the growing congestion in ports and their approaches, the increasing size of ships which leaves less room for manoeuvre, and the increasingly serious consequences of mishaps to ships carrying large and dangerous cargoes. Apart from safety considerations, effective handling can have economic benefits by shortening delays at terminals.

Traditionally, merchant ships have stopped by stopping engines, or turning them astern; they have steered by means of a stern rudder. But the large modern tankers can take a quarter of an hour to come to rest, with engines at 'full astern'; and any single-screw merchant ship is virtually unsteerable, at mercy of wind and waves, while her screw is turning astern. On top of this, even when steaming ahead, steering behaviour is markedly degraded by shallow water, and as ships grow the shallower do our seas appear.

6. (a) *Manoeuvring devices*

The need to improve handling, particularly in craft such as ferries which berth frequently, is already appreciated and a variety of devices have been developed to exert sideways thrust to assist berthing. These however are so far relatively puny; there is now a need for a device which will enable really worthwhile sideways forces to be exerted on a ship while she is stopped or moving slowly, ahead or astern. The eighties will probably see this, indeed they will demand it if the density of shipping continues to grow.

Manoeuvring devices may be developed from existing designs of rudders, lateral thrust units and vectorable propellers; the steerable propeller duct is promising. However, it is quite possible that we shall see entirely novel methods of accelerating water so as to generate the desired forces. We should not reject the possibility of some shore-based mechanism for exerting hydrodynamic forces upon ships in the final stages of their approach to the berth. A loaded quarter-million tonne tanker moving at only a few centimetres per second contains enough kinetic energy to do expensive damage to the stoutest jetty, as some operators know only too well, and measures will be developed by the eighties for monitoring and controlling the final approach with vernier precision.

The transfer of oil from and to loading points in the open sea presents us with a new problem. Before long the North Sea is likely to be well and truly littered with fixed obstructions, production towers and the like. Navigation will become more complicated and manoeuvrability more in demand. The ability to pick up a buoy and ride steadily to it in all weathers will become important. Ships will need to assist with their own engines and thrusting devices, to neutralize the effects of current and wind so as to off-load the mooring. Engines giving continuous controlled thrust at low revolutions will be needed – a requirement defeating the present diesels with fixed-pitch propellers. Rudders and thrust units will need to work under these conditions.

(*b*) *Training*

It was pointed out above that ship handling depends upon the Master's skill as well as upon the physical design of the ship. Skill depends upon training, a largely haphazard matter up to the present. It is likely that by the eighties ship-handling training will have been improved and systematized by the use of simulators, shore-based machines programmed to reproduce exactly the manoeuvring behaviour of ships under various conditions of draught, water depth, current and so on. The hydrodynamicist's contribution will be to predict the required manoeuvring parameters, including those of ships as yet unbuilt, so that the officers can practice 'handling' her on the simulator while the ship herself is still in the builder's yard.

6. RESEARCH IN SHIP HYDRODYNAMICS

Europe, Japan and the U.S.A. are well provided with ship hydrodynamics research establishments, commonly known as 'ship tanks'. Indeed, in Europe it can even be argued that there is a superfluity of conventional towing tanks. There is already a degree of cooperation: it is possible that by the eighties we shall see a measure of concentration and specialization.

One feature of the shipping industry has up till now militated against the exploitation of the full potential of hydrodynamic research. This has been the persistence of owners in ordering ships to 'one-off' designs, which has meant that much laboratory time has been taken up with what amounted to a succession of proving tests ordered by the shipbuilders rather than true research. Often too these tests were commissioned at so late a stage that shortcomings shown up by the laboratory work could not be corrected at the ship because construction was too far advanced.

The recent trend to building series or classes with similar hulls promises an improvement. There will be fewer designs tested, but the costs of each design tested can be spread over more ships. This means that model work can be more thorough, and properties which previously were scantily investigated in routine jobs, if at all – such as wetness, slamming and steering – can now be gone into in detail.

There is also already a tendency for owners, as distinct from builders, to commission research work, and to commission it before building orders are placed. Some such orders have a considerable 'true research' content of general hydrodynamic interest. The better timing means that the laboratory has far more chance to help with hull design. The concentration of the owning industry, with the resulting coalescence of owners' technical staffs into fewer but larger groups, and a tendency to employ more highly qualified staffs, means that technical problems can be gone into more deeply. There is too an important difference between the approach of an owner and of a builder to the laboratory; the builder is inclined to confine his interest to the speed achieved at the acceptance speed trials which are carried out in calm water on the measured nautical mile. The owner, however, hopes to operate the ship in all conditions over many years, and his interest extends beyond fair weather trials to service in all imaginable sea conditions. The author feels strongly that early cooperation between laboratory and owner's technical staffs promises mutual benefits and more effective exploitation of available tank facilities and staffs.

Another trend in hydrodynamics research deserves mention; this is the emergence of the U.K. Government and national bodies as 'customers' for civil ship research. Responsibility for legislation affecting marine safety has lain with the Government for many years. Recently, and more especially since the advent of I.M.C.O., such legislation and the associated international negotiations have increasingly demanded a background of technical information. For some of this Government has had to resort to a research establishment. Examples of work carried out under this head are the recent survey of sea traffic in the Channel, and an experimental programme to explore the relation between capsizing, stability and freeboard in damaged passenger vessels. With the growing complexity and unavoidable Government involvement in sea transport, research of this type in direct or indirect support of legislation seems likely to increase.