VI

HYDRODYNAMIC BARRIERS IN SHIP DESIGN

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A discussion of some of the related unsolved problems and the continued necessity for the application of empirical methods to the design of ships.

The naval architect is surrounded with barriers of varying degree of density in practically every phase of his work in ship design that is related to hydrodynamics. Barriers exist in the theory and mathematics, the experimental work in the laboratories. the full-scale performance of the ship, the weather and the sea its affects, and in a large measure in custom and tradition. Certain hydrodynamic barriers that exist for the surface ship vanish in the case of the submarine.

Aside from the barriers associated with hydrodynamics there is an economic barrier. The very physical size of a ship and its cost and time required for construction, constitute a most formidable barrier to progress. The aircraft designer is seldom expected to produce a successful plane in his first try. Several experimental planes are built and tested before a prototype is reached. Not so with a ship, every piece of equipment and machinery must be tried and true so that the very first prototype will be successful or very nearly so in meeting all the essential requirements.

The demands for the attainment of more advanced properties in our ship designs are becoming more and more urgent due to the changing technology of the times in which we are living. The fact that the art of shipbuilding is among the oldest known to man has in a large measure handicapped the scientific side of our work. In a period when newer industries were making rapid progress through a more scientific approach the need for theoretical research was not considered an essential part of the naval architect's work because great success had been attained by evolution and watchful attention to the performance of full-scale ships. Fortunately, or possibly unfortunately, our predecessors were so very successful in meeting their requirements on the basis of good judgment that the need for more extensive theoretical work was not readily apparent. Ship hydrodynamics was, in a sense, a plaything for the theoretical minded but of little import to the practicing naval architect. In the meantime the competitive aircraft industry has come along in giant steps largely on a basis of theoretical and applied research. Because of this, and the many advances in the fields of physics, we too feel compelled to encourage the scientific approach.

In this brief discussion reference will be made to a few of the important barriers we have been dealing with in the past and to some of the more important ones which may limit our progress now and in the future. The specific areas of importance are speed, frictional and wave-making resistance, rough water performance, maneuvering, flow noise, and cavitation.

To obtain speed at the least cost has been one of our ever present problems and it is in this area that our experimental towing tanks have made their greatest contribution to our work in hull form and propeller design. The price of ship speed is often not fully realized, especially when we note the tremendous progress that has been made in the speed of airplanes. Because of this progress in aviation it is often wondered why ships seem to be standing still in this matter of speed increase. The answer is quite simple. For example, to double the speed of a 50,000 ton displacement ship from 30 knots to 60 knots would require an increase of power by a factor of about ten. Which in this case would mean increasing the power from 140,000 to 1,400,000. In this example the displacement was assumed constant. This, of course, could not be so unless the increased power and fuel requirements could be met without increase in weight and space. To some degree this has been the case in surface ships because of the improvements, over the years, in the reduction of the machinery fuel rate and weight per shaft horsepower. Much of our increase in the speed of surface ships can be attributed to the improvements in the machinery plant rather than to any recently gained knowledge of ship hydrodynamics. On the other hand, the speeds of submarines have been increased because of recent work concerning hydrodynamics of submarine hull forms.

Frictional or viscous resistance has been under constant study since 1872 [1], [2], [3], [4], and we are still in doubt as to the exact nature of this phenomenon. While the correct understanding of frictional resistance cannot be considered a serious barrier, its importance should be recognized. This kind of resistance [3] accounts for some 50 per cent of the total resistance of many of our surface warships. Ship trials have indicated that the effect of different paints may cause as much as 15 per cent variance in total power, or some 30 per cent in skin friction. When the amount of power being developed in such ships to overcome frictional resistance is considered, the necessity for an understanding of the mechanism of skin friction should be obvious. Not only does the nature of the surface affect the drag but the wake is also changed, which is reflected in differences in the propeller performance. In the case of submarines practically all of the submerged resistance is frictional or viscous drag. To reduce this drag has intrigued many research minds and some thought has been given to the possibility of maintaining laminar flow by boundary layer control.

It is in the area of wave-making resistance where the surface ship meets some of the most formidable barriers, and it has been one of our great aims in life to avoid or reduce this type of resistance. The determination of the wave-making resistance has been one of our most active fields for theoretical and applied research. We have had to rely entirely on the results of model tests, singly and in groups or series, for the specific values of the effects of wave making on resistance. The basic problem results from the failure of the residual resistance coefficients to follow a simple law for different speeds and hull forms because of the change in the flow pattern with speed. Remarkable results have been obtained from the application of mathematical methods to the investigation of wave-making resistance of well-defined ship hull forms. The results of these investigations have reached a stage in which they have been correlated by experiment; but direct application to problems of actual surface ships have not been realized as yet [5], [6], [7].

An important property which has been well established is that maximum values of the residual resistance occur in Froude number (speed-length ratios) ranges of practical interest. The critical $V/\sqrt{L}$ values at which the maxima or humps occur are close to 0.8, 1.0, 1.5. Most of our large ships are limited in speed because of the great increase in power required to drive them beyond the speed-length range of 1 to 1.25. At the present time we see little likelihood of breaking down this barrier to high speed in large ships. As a point of interest I would like to mention that the fast ocean liners operate at speeds close to $V/\sqrt{L}$ of 1.0 in smooth water.

The two most obvious motions of a ship in a seaway are pitching and rolling. Rolling can be the more violent of the two and in a heavy sea a captain will change course to reduce this violent motion. Such a course change will result in increased pitching but this can be controlled to some extent by speed reduction. In rough water a surface ship may be forced to slow down for several reasons and pitching is probably the principal one. Pitching exaggerates nearly all causes of speed loss. It leads to shipping water over the bow, slamming, and increased resistance. The point of greatest loss of speed and the greatest amplitude of pitching occurs as the wave lengths approach the ship's length, [8], [9]. [10].

On the basis of our present knowledge there is little we can do to greatly improve the rough water performance of a conventionally designed ship. The evidence, though meager, seems to indicate that minor changes in hull form, based on optimum performance in smooth water, will not materially improve the rough water performance. Obviously we must consider major changes in concept in order to attain, for example, the same smooth performance for a surface ship in rough water as for a submerged submarine. Much thought is being given to this problem, as evidenced by recent papers on ship speeds and motions in regular and irregular seas [11], [12]. It is possible that we may be at the threshold of some practical progress in this area [9], [13], [14]. Successful control of rolling, to a reasonable degree, may be accomplished by means of controlled fins [15], [16], [17]. Pitch damping is also under study and some success seems indicated by the use of hydrofoils at the bow. These and major changes in hull form above and below the waterline may produce a surface ship with considerably improved performance characteristics in rough weather.

The maneuvering of ships has always received much practical attention. For many years what little we knew came from full scale tactical trials which were quite common with naval vessels. From the designer's standpoint little theoretical advance was made in the way of making it possible to calculate the turning and steering properties of a ship. At the present time it is still necessary to rely upon an empirical approach to the calculation of tactical diameter and directional stability [18], which is an important element of course keeping. Model testing techniques have been developed to a point where we can determine, with a high degree of confidence, the full scale performance of a ship or submarine. However, it should be noted that here again, as in wave making resistance we depend on the model test results rather than on a theoretical solution of the turning problem.

It is still practically impossible to determine, in the absence of specific model tests, the force and moment characteristics of a ship [19]. The problem is complicated by the fact that ships operate at the interface of two different fluid media and also by the complex geometry of ship forms. Complete theoretical treatment is therefore rendered very difficult.

Great advances in the field of electronics have also affected our outlook and trends in design. Electronics has made possible completely new evolution in missile design, provided long range electronic eyes and ears which have affected the topside as well as the under water parts of ship designs. The influence of radar is readily apparent by comparing the topside structure of any modern naval surface ship with one of 20 years ago. Sonar likewise is revolutionizing the design of naval vessels. The capabilities of electronics have influenced the need for control of the motions of surface ships and below the sea surface they have brought about the demand for reduced noise, from any source, which may be transmitted through the water. While much noise is associated with machinery and other components in the ship it is the hydrodynamic noise that is one of our main concerns. This noise is caused principally by flow conditions which produce cavitation, separation, and vortices. This is one hydrodynamic barrier which is particularly important to the submarine.

The exact mechanism associated with the generation of noise by flow over the hull of a ship is not too well understood. Flow into the propeller, and propeller location relative to the hull and other structures, are known to be important elements in the noise problem. The problem is so complex that thorough theoretical research is needed to guide our progress in noise reduction.

The determination of the physical quantities which influence cavitation inception is another one of our important needs [20], [21]. [22]. The development of hydrofoil shapes in which cavitation is delayed or avoided entirely has shown much progress due to the work done by the aeronautical laboratories and by our model towing basins. Cavitation is an important area for continued study particularly in connection with noise problems, our efforts to reduce cavitation erosion, the improved performance of control surfaces and the design of flight foils of hydrofoil craft.

We have always had a great deal of help from many contributors on the theoretical side of naval architecture. Their analytical efforts have increased our understanding and confidence concerning the empirical methods we are accustomed to use by necessity. Unfortunately, however, the laboriousness of the calculations and the inability to readily fit the calculations to our actual hull forms has been a great barrier to the advance of theoretical and mathematical solutions to our problems. It does appear that the burdens of laborious calculations can now be lifted from the human computer or "humac," as we delight in classifying him, to the more rapid electronic computers such as "Univac," "Busac," etc. Now this may appear as being a case of not using what we have and know already. This is not so. For example, even where we know the definite theory and mathematics, as we do in the hydrostatics of ship design, it has been found that electronic computers at present are of but little help to the naval architect.

In the Bureau of Ships we have designed an electronic computer to help solve some of our problems in hydrostatics but at present only in a manner similar to mechanical integration. What appears to be required in the case of hull form design is a completely mathematical method of designing.

A mathematical method of defining hull form would undoubtedly tie in with developments in the hydrodynamic theory and, by a process of optimization of essential elements, the hull form parameters could be directly selected by the naval architect to meet his requirements. Progress in this direction has been slow considering the many years during which effort has been expended on this problem. However, with the many newly developed mathematical tools, particularly in the realm of advanced statistical analyses, and with the development of electronic computers, analogues, and allied devices, it at last begins to appear that we may yet have an essentially mathematical approach to hull form and the solution of problems concerning speed, ship motions and predictions of other performance features.

The lack of basically accurate information has not handicapped the naval architect in the past because there was always enough approximate data available for him to carry on in a reasonably efficient fashion. The barriers he was faced with were concerned with modest speed and other performance requirements.

An important point which should be stressed is that theory alone does not help the naval architect in creating a basic design. He must have, in addition, some basic numbers that he can latch onto in formulating the basic design concept of a ship. These numbers must be related to each other by a set of parameters which are basic to the phenomena which are to be emphasized in the design.

It is realized that the steps from theory, to basic parameters, to numbers are probably the most difficult and monotonous jobs in research work. However, once the proper parameters and numbers have been established, it is the most rewarding part of research work insofar as the naval architect is concerned. The Froudes, Wm. and his son, R. E., and D. W. Taylor had the genius to express their findings in terms of parameters which made it possible for the naval architect to detect trends and to correlate his own meager data collected from smooth water tests of full scale ships and models. To this day much of our work in our experimental laboratories has been a strengthening of their original concepts.

At the present time there is under preparation a complete review by Captain H. E. Saunders of hydrodynamics in ship design [23]. These texts should provide us with the most complete assembly of reference material for the naval architect that is available anywhere. It is believed, however, that while some additional light will be given on the barriers referred to in this paper, the areas of uncertainties and need for further study will still be largely as has been indicated in this discussion.

In closing let me suggest that some of our hydrodynamic barriers might be reduced by developments outside the field of hydrodynamics. Take the case of the limited endurance which has long plagued the designer of surface ships and submarines. With the advent of nuclear propulsion, this barrier has been largely circumvented. We have only begun the exploitation of nuclear propulsion in submarines, but just this one development has given us a type of ship relatively free from hydrodynamic barriers.

From the foregoing discussion it is apparent that the several barriers to progress in naval architecture are largely interrelated and quite complex. This is true of most scientific work when it once passes the rudimentary stages. It almost seems that 90% of the progress is made in the very first crude step. The man who evolved the formula for the flexural stress in a beam, for example, $S = \frac{My}{I}$ provided a theoretical tool which permitted the creation of many structural wonders, and all the modern research of the past 50 years in this field has refined our design approach but little. The parallel with hydrodynamics is obscure because the latter science has proven more complex and less tractable to simplifying assumptions, but it is real nevertheless, and the initial strides in understanding made by Froude, Taylor and others are not likely to be equalled by all our high powered modern techniques. We have only the 10% which they left us to play with. The challenge nevertheless is great and the 10% looms large in the highly competitive world of today.

As a final thrust for the future I would like to present a few questions which were asked by Admiral E. L. Cochrane in 1954, as a means of emphasizing the problems we face in this matter of barriers and the work that needs to be done.

What are the forces acting on a ship at sea as compared to those acting upon a model in an experimental towing tank?

What does happen to a ship's speed in rough weather?

What happens to a naval vessel's weapons platform or flight deck in a storm?

What does happen to a ship in a really rough storm?

These are not new thoughts, in fact they are very old, probably as old as when man first ventured out to sea. Questions similar to these must have been in the mind of Brunel, the designer of the "Great Eastern," when he requested William Froude in 1860 [24], to investigate the probable sea-going characteristics of that ship.

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Abbreviations

INA	Transactions of the Institution of Naval Architects, London, England.
SNAME	Transactions of the Society of Naval Architects and Marine Engineers, New York.
NEIES	North-East Institute of Engineers and Shipbuilders in Scotland.

DISCUSSION

H. E. Saunders

If I may seem a bit critical of some of the author's remarks it is not because we have a different basic thought on these items, but because we look at them a little differently.

Mr. Niedermair said that certain hydrodynamic barriers which exist for the surface ship vanish in the case of the submarine. This is a pure submarine, entirely submerged.

He mentioned hydrodynamic noise, which I think all of you can visualize. However, if you think that just going down in a pure submarine, and getting below the surface, eliminates some of these problems, you might try calculating the submergence depth at which separation at some point disappears, if it does disappear. I am talking now of a separation which occurs at some place on the submarine when it is at or near the surface. Just try this for breaking one of the hydrodynamic barriers.

It is true that in the old days naval architects got along with very little in the way of an analytic approach, relying on practical experience and intuition. That was possible, because if the ship didn't behave the way you wanted it to, well, you just stopped and tried to figure out what to do next. But unfortunately, the airplane designer, or pilot, if he gets up in an airplane, can't quite do that. He has to keep on flying and to figure out, if he can, what is going to happen until he gets back down to earth again.

Mr. Niedermair made the comment that it was the development and the use of the analytic approach in the aircraft industry, and all of the things that went with it, which stimulated us to do likewise in naval architecture. I would like to think that this is so, but there is a long period of relative inaction between what the airplane people were doing back in the 1910's and what we are doing now in the 1950's.

What really poked us from behind, to use a frank term, was the realization of the fact that the empirical approach was just no longer adequate. We had problems to be solved which could not be solved by the engineering knowledge then in our possession. Nor could we solve them by intuition, or from the seat of our pants, if you want to put it that way. We had to find some better way of getting answers.

These problems faced us very critically during the past war. Perhaps because of this situation a great many of us realized that we had to start *thinking* about the problems; we had to apply the analytic approach. And that is what we are doing now, thanks to the efforts of a great many people and to conferences of this kind.

What Mr. Niedermair said about rough-water performance is true, namely that minor changes in the form of a ship do not appreciably affect its behavior in a seaway. Nevertheless, we have in this country, in the last few years, produced a ship, a big ship, which has phenomenally good rough-water performance, particularly in regard to maintaining speed in heavy weather. This ship not only can go faster than any other large ship in smooth water, but she can pretty much match that performance in anything that the North Atlantic has so far been able to put in front of her.

Not many of you remember or realize that over forty years ago we did the same thing with a pair of little ships called the *Great Northern* and *Northern Pacific.* They were built before the first World War. These ships were not large ships; they did not have the length that was mentioned here yesterday. Their water line length was only of the order of 520 feet. Nevertheless, these ships in two wars, on the West Coast and the East Coast, in some of the worst weather in the world, were able to maintain schdule in good weather and bad. As a matter of fact, they were able to do almost as well as the *Leviathan* in the first World War, our yardstick in those days. There was definitely something about these little ships that made them good.

One might say that in maintaining speed, dryness, and so on we have surmounted this hydrodynamic barrier. But we haven't, because we don't know what it is that makes these few ships so good. We can't put our finger on it. We have ideas, but not very many of us agree on anyone idea. And we won't produce the better ships until we know why the ships already built were so good.

The *Albacore* was mentioned here yesterday. She is a remarkable pure submarine, no question about it. But the problem of designing that ship for low resistance was not particularly acute, because we had a great deal of previous experimentation, previous knowledge back of us in the way of work on airships, in the earlier years of this century. We knew more or less what an optimum pure submarine would look like. The *Albacore,* incidentally, isn't too different in shape from the submarines that were built over 50 years ago by J. P. Holland.

Now the thing we don't know, and the thing we must know, or must find out, is what does the optimum wavegoing ship look like? Suppose we had no considerations of cost, no considerations of displacement, no considerations of this, that, and the other thing, what is the optimum form of ship for traveling in waves? That we do not know, and that we must know some time or other.

There has been a lot of talk about electronic computers, but don't let us forget that, in general, in order to work an electronic computer we have to have some mathematical formulas. In order to derive the mathematical formulas we must know the psysical processes. In many cases I am afraid that we have not known the physical processes too well before we ventured out on very thin ice with the mathematics. So we had to go back and try over again.

One last item has to do with this matter of hydrodynamic barriers on the new type of submarines. I am talking about the ones that are not atomic-powered, but atomic-fueled only. Propulsion of these vessels is still hydrodynamic.

Perhaps I can best explain what hydrodynamic barriers we are up against by pointing out to you that we work in a very limited depth of water with any of these submarines.

Consider that you are a pilot of a big new fighter plane in the next national emergency. This plane is as large as an existing transport plane. You and your crew are supposed to carry out some attacks, in the course of which you have to dodge shell fire, and to dodge all sorts of missiles down close to the earth. All this time you have the certain knowledge that if you climb, with that airplane, more than say 500 feet above the earth, it will surely explode. One such climb, to too high an altitude, will mean the end of you and your crew, and of the airplane.

This is the sort of problem which we still face with the submarine, regardless of the type of propulsion, or the type of fuel, or the type of power. I am sure that the aerodynamicists and aeronautical engineers, if they were faced with a problem like this, would be very much busier than they are today.

J. F. Allan

I congratulate Mr. Niedermair on his paper, and particularly on the title, which I found stimulating and speculative.

There is an old saying that an engineer can solve any problem in the technical sense, provided he is given time, but time, of course, costs money, and that brings us up against the economic aspect of the matter.

There are two approaches to the situation, one from the service point of view, and the other from the commercial point of view. These two approaches tend to be very different, as from the defense point of view economy is not the first consideration even in times of peace.

When we come to the commercial approach, at least in my country, the ship owner is not interested in technical developments unless he can see that they are going to lead to a clear commercial benefit in what is a very highly competitive industry. It is against that background that I tend to view this question of hydrodynamic barriers. These barriers may also be looked at from two angles. One is concerned with the improvement of existing techniques, and this is of particular interest to the commercial user of ships, and also, of course, to the service user of ships. The other is the more spectacular and revolutionary approach, where quite new techniques may be proposed, and successfully introduced, and these are of primary importance from the service point of view. In many cases they lead to developments which are of great value from the commercial point of view.

The author stated that the improvements which had been provided in propulsion of ships by the marine engineer were much more spectacular than those provided by the naval architect. One must agree with that statement, but we should not forget that the naval architect has been responsible for improvements of the order of 30 per cent in the last 25 or 30 years, and that is no mean achievement.

I mention the friction barrier, which is a very important contributor to the total resistance of the ship, and although a great deal has been done in recent years to reach a better understanding and appreciation of the importance of a smooth surface, I think we still have quite a lot to learn, perhaps not so much in producing an initially smooth ship, but in preserving that smoothness over the life of the ship. It may even be possible that spectacular developments will come along to reduce friction much further. We do not fully understand the detailed mechanism of fluid friction. As regards wave-making resistance that, I am afraid, will always be with us on surface ships, and the only thing one can do is either go down below or get up above.

We have had quite a lot of comments today and yesterday about the remarkable performance of the latest submarine down below, and it may be that there is a future in that direction for cargo carrying, but it would be difficult to persuade passengers to travel in a high speed submarine. The alternative is to lift the vessel above the water on hydrofoils, and considerable success has been achieved in that direction. There may be service applications for such vessels, but I doubt if there will be much big scale commercial application. If you want to lift the boat out of the water, it seems to me the obvious thing to do is to get right up in the air and fly properly.

As regards sea speed, there may be some very interesting developments in that direction in the next few years. Captain Saunders mentioned several American ships which he considered have remarkable sea-going performances, but he admitted that nobody understood why these ships were outstanding.

Roll stabilization has been successfully achieved in the United Kingdom, and the system is now being applied to American ships. Pitch stabilization is more difficult, but a useful degree of pitch damping is possible. With these things accomplished it will probably be reasonable and economic to drive at full speed in bad weather conditions.

I mention again the point I made yesterday, that if a ship is being driven hard in such conditions, it is of the very greatest importance that the control mechanism on roll and pitch stabilization does not fail, otherwise the ship could be in serious difficulty.

May I conclude by recalling a speech which was made at a dinner here five years ago in connection with the International Towing Tank Conference. The then Secretary of the Navy cited the remarkable developments in aircraft, and rather threw down the gauntlet in regard to ships. At the time, the proposals he was putting forward seemed to me rather fantastic, but it may be that in the course of time we will get some way towards achieving them.

F. H. Todd

Mr. Niedermair has given us an excellent review of some of the problems facing the naval architect today.

As many of you here today are working in other fields than ship design, I would like to focus your thoughts on the ship problem by considering the design of a large passenger vessel. The civil engineer has to face many problems in the design of modern bridges, the architect and the civil engineer have to combine their skills in the erection of many modern buildings, whilst the mechanical engineer is concerned with all forms of power plants and other machinery. In the design of a large passenger vessel, the naval architect is faced with all these problems at once, and generally in a more acute form. The ship hull is a much more complicated structure than a bridge because of the variation which is necessary along its length to accommodate various machinery, boiler and other spaces, the accommodation has to include all the amenities of a first-class hotel whilst circumscribed between the sides of the ship's hull, and the machinery plant has to have power equivalent to that necessary to supply a small city with electricity. Add to these the fact that this whole structure has to cross rough and stormy seas at a speed of 30 knots or more, safely, economically and to time table, and you begin to get a picture of the problems which the naval architect has to face and, indeed, has overcome with considerable success in the past.

At one place in his paper, Mr. Niedermair refers to Ship Hydrodynamics as being "a plaything for the theoretical minded." When asked what I do, my wife is prone to reply "research" and when asked to describe this, she describes it as "organized play for adults." As a player in this game, I would like to comment on a few of the points which Mr. Niedermair has raised and on which research work is presently being carried out.

The author has drawn attention to the great effect which frictional resistance has on a ship's performance. For a great number of years now, much effort has been devoted to obtaining surfaces with as low a resistance as possible. It would seem that as long as a surface is very smooth and hard, its exact nature has little, if any, effect upon the resistance. With a hard, smooth paint of this kind, most of the excess frictional resistance on a new, clean ship has in the past been due to seams, laps and rivet points. With the advent of welding, this "structural roughness" resistance has been greatly reduced, particularly where care has been taken to grind off the welds and make them as smooth as possible. On clean, new ships with this type of surface, the additional structural roughness resistance appears to be very small and the resistance approaches that of a smooth plane surface. Two things can spoil this effect. Antifouling paints if carelessly applied can increase the resistance materially, as noted by

Mr. Niedermair. Also, for vessels which spend a considerable portion of their lives at anchor, the resultant fouling of the surfaces by marine organisms can increase the resistance to a very great extent. Our aeronautical friends have achieved considerable success in aircraft by the use of laminar flow wings and the question is often asked whether advantage can be taken of this idea in ships. The degree of smoothness required to maintain laminar flow is exceedingly high and it is doubtful if it could ever be achieved on a ship's hull. Even if it were, excessive care would have to be taken to prevent fouling, as this would rapidly eliminate any chances of maintaining such a flow. Moreover, in the case of surface ships it is probable that the sea near the surface is so turbulent that the achievement of laminar flow is physically impossible anyway. Perhaps the best hope for such success would be in submarines or torpedoes running very deep, where the level of turbulence in the ocean might be very low. There have been many other suggstions for reducing frictional resistance, including the use of soft surfaces similar to those of fish, of various liquids which would be slowly shed and of blankets of air bubbles. It has yet to be demonstrated that any of these can produce lower drags than a hard, clean, smooth paint.

The other important component of resistance in a surface ship is the wavemaking. The amount of this is very small at low speeds, but increases very rapidly at higher speeds and makes the achievement of these speeds very costly. There are two possible ways to overcome this barrier: to go below the surface or to lift the main body of the ship clear of the water by means of hydrofoils. The submerged cargo ship has been considered many times, and there are certain cases where such a craft would be invaluable for military use. A commercial, completely-submersible ship would have many handicaps to overcome in comparison with a surface craft. The hull would be much heavier and more complicated, and for the same available deadweight would have to be considerably larger than the corresponding surface ship. Because of this and the fact that the ship would be completely submerged, the wetted surface would be much greater and therefore at low speeds the resistance would be considerably higher. The advantage of complete submersion on the wavemaking resistance would therefore not appear until relatively high speeds were reached; then the saving in wavemaking would be such as to offset the initial increase in skin friction. There would also be considerable difficulties in the handling of cargo in such a craft, and the most promising developments in this respect would be for oil-carrying vessels.

Lifting the body of the craft out of the water with hydrofoils also introduces many problems in anything but small size ships. In larger vessels capable of carrying any appreciable deadweight, the problem of the size and weight of the foils and their supports becomes a serious one, as does the excessive draft in port when not foil-borne. As such craft, to be of any value, would have to be high speed vessels, the problem of power and its transmission to propellers located deep below the craft also becomes extremely difficult.

In the realm of ship motions, great efforts have been devoted in the past to the reduction of rolling. This is very desirable for military vessels today in view of the many delicate instruments and weapons which they carry. As regards comfort in passenger vessels, it has always been my personal experience that pitching is far more uncomfortable than rolling. Some years ago the Model Basin collaborated with the Naval Medical Services in an effort to determine the cause of seasickness. We supplied instruments and observers to record the pitch, roll, heave and accelerations on certain Navy transports running between New York and Europe. The Medical Corps provided doctors who administered different anti-seasickness drugs to the troops in the various compartments on the ship. There were many confusing features in the results, but one fact certainly did seem to be quite clear. As the weather deteriorated, the first cases of sickness appeared at the ends of the ship; as the weather got worse, the degree of sickness in the end compartments increased and the incidence spread inwards towards midships. An analysis of the results appeared to give very good correlation between the incidence of seasickness and the vertical acceleration. Any attempt to reduce pitching motion by means of fins or other devices located towards the ends of the ship introduces much more severe problems than the reduction of rolling because of the much greater forces and leverages involved. It is interesting to note that despite these problems serious consideration is now being given to the fitting of such fins, and we have carried out experiments at the Model Basin which indicate that reductions in pitching can be achieved by such means and that the forces acting on the fins, while large, can still probably be handled. Of course, the achievement of substantial reductions in pitch by such fins will contribute not only to greater comfort on the ship but will also minimize the reduction of speed, the damage due to slamming, and if the shipping of green seas can be avoided, then damage to superstructures should also be greatly reduced.

The recent emphasis on rough water performance has demonstrated that reduction in speed is normally dictated by the necessity of avoiding excessive ship motion rather than by lack of power. The choice of a ship's lines should no longer be made solely on the basis of good smooth water performance. It may well be that some of the latter will have to be sacrificed in order to achieve the best performance under average sea conditions. In the relatively slow speed cargo ship, for example, the best smooth water performance can generally be achieved using full bow lines with a very fine stern. If this tendency is overdone, however, the ship may give disappointing results at sea and lose speed quite rapidly. Research into the seakeeping qualities of ships has been greatly handicapped through the lack of proper test facilities but fortunately this is now being remedied.

Although Mr. Niedermair's paper is concerned with hydrodynamic barriers of ship design, I think that the overcoming of such barriers is partly dependent on overcoming some economic barriers. Mr. Niedermair comments on the rapid strides made by aeronautical engineers and this is in large measure due to the immense sums of money that have been spent in research and development in the field of aeronautics. In comparison, the money devoted to research in hydrodynamics is almost negligible. In the matter of experimental craft, too, the naval architect has been much too conservative in the past. The aircraft industry thinks nothing of building experimental craft at great cost to try out new ideas, but most new ships, whether of naval or merchant type, are usually expected to pay their way when completed. In recent years, the value of a ship designed primarily as an experimental craft has been well shown by the success achieved with the submarine ALBACORE. It is to be hoped that in the future more experimental ships will be built in order that the naval architect may have opportunities similar to those of his aeronautical colleague to try out new ideas without the burden of having to make the ship pay its way in the military or commercial sense.

H. de Luce

As Mr. Niedermair brings out in his paper, we Naval Architects actively engaged in designing ships have relied almost entirely on full scale experience and on empirical research. On this basis, over the years, we have succeeded reasonably well in producing war ships and merchant vessels of increasing size, speed, and fitness for their intended services.

I have no doubt but that empiricism will continue to provide the solutions to our problems for some time in the future. On the other hand, the interpretation and evaluation of empirical data and experience may certainly be misleading without theory to establish the significant parameters and their relationships. And, looking to the future, it seems to me to be only reasonable to expect that the configuration of ships will undergo as radical a change as has occurred in aircraft with the advent of supersonic speed. In developing this ship of the future, we are certainly going to need all the guidance we can get from fundamental theory and basic research.

I think all of us interested in the design of ships can feel great satisfaction in this symposium. To me its significance lies not only in its coordinating force, in terms of hydrodynamic research, but in stimulating such research and its practical application by bringing together physicists, mathematicians, experimenters and engineers. We must improve the communication between these groups if we are to properly define our problems, plan the appropriate analytical and experimental research, and then apply, in engineering terms, the results of this research. Our several talents and interests are all needed if we are to produce ships to best serve the future military and economic needs of the Navy and the Merchant Marine.

May I say that I feel it particularly appropriate that a naval architect of Mr. Niedermair's stature should present a paper before this symposium. May I also say I am very happy to have this opportunity to make these brief remarks.

K. S. M. Davidson

I am afraid I must take issue, not so much with the statements in this paper, as with one or two of the implications. I dare say John Niedermair suspected I might.

In the first place, I do not like the word "barrier." I do not think the aeronautical people were very smart when they coined that word, and then very soon pierced the barrier they were talking about. The naval architects are not confronted with anything like a real barrier to increasing the speeds of ships. A good deal of power is needed, but we have in fairly advanced states of development various means of getting much more power without materially increasing the machinery weights. One hears people these days talking soberly of building inter-continental missiles and satellites that will circle the earth. Yet when one talks of increasing ship speeds by 25 or 50 per cent, the same people seem apt to think that the world is coming to an end.

Personally, I do not believe that there is a very great difference between commercial and military requirements for speed. It is a matter of second-order differences. I think it is high time that the Western Allied Powers began to give ships enough speed to permit them to run away from submarines. We nearly lost two wars because of submarines and everybody knows that submarine speeds are going up. I say that it is quite feasible to give cargo ships very much greater speeds.

I promise to push as hard as I can to get things going, if somebody will set to work to design a really fast cargo ship, instead of talking about how difficult it is to do.

Mr. Niedermair said that ten times the power is needed if speed is increased from 30 to 60 knots. That is true, provided however that one insists upon building the same ship. But the knowledge has been available for a long time that reducing the fullness of the hull reduces the wave-making resistance enormously. I do not have exact figures here, but if one does not insist upon 60 knots and is satisfied with say 45 (which is, after all, a fairly respectable speed) and if one makes the hull a good deal skinnier than is usual (which is not impossible to do), less than five times the power is required.

I submit that there is a considerable incentive to go this far, first from the military point of view, and second from the commercial point of view. There are various indications from recent studies to show that the cost will be less than many people are inclined to think.

I would like to see work started now on the design of a cargo (not a passenger) ship of 45 knots, and I would like to see plans laid to build such a ship very soon, as an experimental ship looking to the future. It would make a challenging research target.

R. W. L. Gawn

We are fortunate in having such a searching paper from Mr. Niedermair which reflects his outstanding ability, ripe experience and fine achievement in ship design.

Much research by theory and experiment has been devoted to the improvement of the operational qualities of ships. Emphasis is strongly veering towards the development of the best shape of hull and distribution of load for seagoing conditions rather than for calm water, to which much attention has been devoted in the past. This is evident from the new facilities being constructed in America and Great Britain and that recently completed in the Netherlands for realistic investigations of seaworthiness and ship motion. There is also a rapidly expanding interest in cavitation and additional facilities for investigating this phenomenon are being provided in various countries. The boundaries of research are being thus extended in order that ships may clear the hydrodynamic barriers as far as possible. We may look forward to faster, steadier, handier and more economical ships, although advance will continue to be circumscribed by the physical limits imposed by the density and viscosity of water and of air and of the vapour tension, gas content and surface tension of water.

Much fuel is squandered by ships in overcoming the skin friction resistance of the hull and to a smaller extent the propeller. There has been an improvement in this respect of about 10 per cent following the advent of welded hulls. If a ship could be built as smooth say as bonded plastic asbestos, research informs us that the frictional resistance of a clean hull might be further reduced by say 10 per cent. Luxurious animal and vegetable life thrives on a ship's hull to such an extent that the frictional resistance may be increased by 25 per cent when six months out of dock. This is about one half the increase that obtained some years ago, which is one indication of the achievement of research. Thus the door to the barrier of viscosity is being pushed slowly open.

The inventor seeks to break through by clothing the ship with air but is defeated by the excessive power of the necessary air compressors. Laminar flow and boundary layer control offer entrancing theoretical prospects but formidable problems are presented including a revolution in shipyard practice to obtain the necessary smoothness of hull finish and the annihilation of the barnacle and its fellow travellers.

Rough weather can severely limit the overall operational performance of a ship due to the consequential oscillations in the six degrees of freedom, shipping heaving seas over the bow and exposed operational positions, and by reducing speed.

It may be necessary to ease the speed below that obtainable from the propelling machinery to reduce the ship motion and prevent structural damage. Generally conditions are most severe in seas of a length somewhat greater than that of the ship, for example, studies on a model of a carrier about 700 feet long indicated that the speed would be a minimum in steep seas about 800 to 900 feet long and about 40 per cent of the full speed. Ninety-five per cent of the full speed could be obtained in waves about half the critical length. By and large the severity of the motion changes similarly with the length of wave. Detailed investigation indicated that the probability of the carrier meeting conditions limiting flying operations was on a conservative basis 18.5 per cent in the North Atlantic and 12 per cent as an average of all the oceans of the world.

If the ship were twice the size, namely 1400 feet length the probability would be expected to be about halved, although this has not been examined in detail. Thus a definite if not very striking gain in sea-keeping qualities would be expected if the size of ship could be increased well above the present maximum length of about 1000 feet.

Ships generally are much smaller than the few giants of about 1000 feet length. The probability of objectionable motion is greatly enhanced as critical seas are more frequently encountered. Model experiments have shown that the pitch and heave amplitudes can be reduced by a worthwhile amount by suitable shape of hull ('V' sections forward and flat sections aft are one example) and by about 50 per cent if longish passive fins are fitted. The damping varied with speed of model and size of wave. The relative gain was less in short waves but the motion was then small. Thus there could be a considerable advance if the fin device were considered practicable, although this would be well short of the remarkable achievement of active fins in reducing roll. Comparable improvement in pitch and heave could, in principle, be obtained from active stabilization but at the expense of excessive size and weight of the equipment. Thus for the present it is suggested that the search should be for limited stabilization of surface ships rather than the ideal target of complete stabilization. The wave barrier is of course completely avoided by the submarine when operating at deep submersion.

Man in the urge for speed has succeeded in travelling nearly 200 knots on calm water but only as a record sprint. Thirty to 35 knots is about the present limit for large ships and the speed of intermediate and small vessels is commensurate with 40 knots. Confronted by ocean waves, speed is greatly reduced and very few ships have succeeded in crossing the Atlantic at 30 knots. The price of speed is high, the real physical barrier being the large density of water. None will deny the scope for improvement both in steadiness and speed. The Author's paper and the wide net cast by this Symposium encourages the hope that achievement will not fail for lack of skillful effort.

M. C. Eames

Mr. Niedermair, and some previous speakers, have made reference to the hydrofoil craft. As is likely to be better known by readers of popular picture magazines than by students of technical transactions, the Defense Research Board of Canada is sponsoring a research project on the development of a particular type of hydrofoil craft at its Naval Research Establishment at Halifax. Since in the design of the craft, an entirely new form of hydrodynamic "barrier" has to be considered, it is felt that the following notes may be of interest.

While the most ardent supporter of the hydrofoil craft would agree with Dr. Allan and others, that in general if one wishes to attain high speeds, one should take to the air completely, there nevertheless exists a regime in the speed-size field of transportation where the hydrofoil craft can show a definite advantage in terms of power economics. Moreover, certain military advantages are apparent outside this region where the hydrofoil craft presents the most economical means of transport.

The existence of such a regime, and the state of the art up to 1953 have been comprehensively recorded in a paper by Buerman, Leehey and Stilwell before the Society of Naval Architects and Marine Engineers in 1953, and the Institute of Marine Engineers in 1954. In general it may be said that subsequent advances have been a matter of detailed improvement and the collection of data rather than one of basic changes of principle.

Mr. Niedermair has referred to the "barrier" in speed which results from cavitation of the lifting hydrofoils. Particularly in surface-piercing hydrofoil configurations, however, a further "barrier" can present problems at a lower speed than that at which the hydrofoils begin to cavitate. Drawing an over-simplified picture, it is clear that cavitation will commence when the pressure on the upper surface of a hydrofoil has dropped to the vapor pressure of the surrounding water. However, in general a much lower speed will suffice to reduce the pressure on th upper surface to that of the atmosphere, and once the pressure falls below this value the phenomenon of ventilation can occur. This is the process by which air is drawn down the upper surface of the hydrofoil, possibly via a supporting strut, resulting in much the same effect on performance as a well developed state of cavitation.

The mechanics of ventilation has received little fundamental study in the past, and the process is not yet fully understood. While means of prevention and cure for particular hydrofoil craft have been successfully developed, the "barrier" cannot be said to have been truly overcome. The essential reason for this statement is that the scaling laws applicable to the phenomenon remain incompletely understood, and until they are fully appreciated the extrapolation of proven results and methods on small test hydrofoil craft to full scale prototypes will be subject to a degree of uncertainty.

It is in the hope of stimulating further interest in the study of ventilation that these remarks are made, and it is considered a significant addition to Mr. Niedermair's most interesting survey because it is probably the least understood of all hydrodynamic "barriers."

E. Moberg

Mr. Niedermair's excellent talk has brought to mind a hydrodynamic barrier which recently appeared and eventually was lifted, and is the type of practical problem which I believe will interest those who are not already familiar with it. A recently designed ship experienced a severe hull vibration during her builders trials, and also on subsequent trips. This vibration appeared at about ¾ speed, and at top speed increased to a severe level about 4 times the lower value. It was a constant frequency hull mode which was being excited. This mode was of lower frequency than either the shaft rotational or blade impulse frequency, which are the more common troublesome hull vibration frequencies. Considerable instrumentation and several sea trials later it was agreed by all involved that the rudders appeared to be transmitting the exciting forces to the hull. These ships are twin screw two-rudder ships, and the rudders were originally designed so that the rudder trailing edges were toed in forming an angle of 3° with the ship's centerline. As one attempt at a solution, adjustable rudder links were made so that the toe-in angle of the rudders could be varied. A series of runs, with toe-in angles varying from 4½° toe-in to 3° toe-out was conducted. These produced a family of curves which showed very severe vibration at 4½° toe-in and a quiet ship between 1½° and 3° toe-out. Subsequently, the rudder angles were set at 1½° toe-out, and no further vibration trouble has been experienced. Upon drydocking of this ship after only 1800 hours sea operation, about 20 of which were in the upper ¼ speed range, it was seen that nearly all of the paint had been removed from the suction faces of the rudders, almost as if sand-blasted, while on the pressure face only small areas in the maximum thickness section had been removed.

In closing, I will say that such problems of this nature, and their solutions, should, and do, stimulate research so that practical experience can be related to theoretical and empirical data, thus providing ship designers with more effective tools with which to work.

J. C. Niedermair

The primary objective of the paper was to indicate the many uncertainties which exist in the basic knowledge of hydrodynamics related to the design and performance of ships. This objective is amply supported by those who so kindly contributed to the discussion of the paper. Some exceptions were taken to a few of the statements made in the paper. These exceptions were particularly in regard to the cost of speed and the emphasis on the lack of basic theory. Fortunately, there is no disagreement in principle but only with the relative degree of importance which should be placed on the various "barriers".

I am grateful for the comments contributed by Dr. R. W. L. Gawn, chairman of the session at which this paper was presented, Captain H. E. Saunders, U.S.N. (retd), Dr. J. F. Allan, Dr. K. S. M. Davidson, Dr. F. H. Todd, Mr. H. deLuce, Mr. M. C. Eames, and Mr. E. Moberg. Their comments form an important addition to the paper. Rather than a personal reply to these comments I prefer to direct attention to Mr. Gawn's discussion wherein he sums up the situation regarding the current status of hydrodynamics in ship design and performance.