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

The Prediction of the Manoeuvring Characteristics of Vessels [and Discussion]

R. K. Burcher, G. Victory and J. E. Ffowcs Williams

Phil. Trans. R. Soc. Lond. A 1991 **334**, 265-279
doi: 10.1098/rsta.1991.0013

The prediction of the manoeuvring characteristics of vessels

By R. K. Burcher

Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, U.K.

The paper considers the requirements for the determination of the manoeuvring and control characteristics of marine vehicles in design and subsequently in operation. A review is conducted of the methods currently available to determine manoeuvring characteristics. These include physical model tests, empirical estimation methods based on previous ship data and various calculation methods. Consideration is then given to the prospects of a computational method being successful in view of the difficulties and complexities of the fluid flow problem for a body in general motion and with a free surface. The paper concludes with a discussion of the virtues of the derivative approach, commonly used to describe and simulate the characteristics of ship response; and debates whether a more direct approach to the determination of ship responses in which derivatives are combined may be an avenue for further research, noting that some approaches of this type appear to be promising.

1. Introduction

The purpose of this paper is to review the techniques currently available for the prediction of the manoeuvring characteristics with the particular viewpoint of design.

The task of design is to define a vehicle to transit on or in water for the transportation of cargo, people or equipment to be used at sea.

In the present context it is the vehicular characteristics of power, motions, structure and control which matter most (figure 1). The size of the craft is mainly dictated by the transport requirements and it is the proportions and shape over which the designer can exercise some control. With so many interactions to consider it is usual for these shape parameters to acquire some finality early in the design. There is therefore a need for some form of reasonably accurate prediction methods to be available at the stage of design selection.

Despite the inherent complexities of hydrodynamic behaviour, reasonable methods are available for the initial estimates of resistance and powering performance and ship motion characteristics in a seaway. Though such methods may not be exact in absolute terms they provide a useful comparative performance tool to aid design choice.

The situation regarding the assessment of manoeuvring characteristics appears much less satisfactory. There appears to be little in the way of a validated technique to ensure that a design has acceptable characteristics or even that the committed features of a design allow sufficient scope for later detailed investigation.

Phil. Trans. R. Soc. Lond. A (1991) **334**, 265–279
Printed in Great Britain

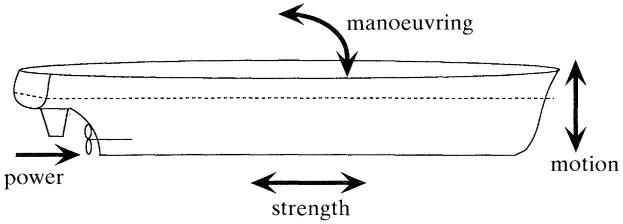

Figure 1. Aspects of preliminary design.

2. The requirements for the manoeuvrability and control of waterborne vessels

Powering is a directly quantifiable topic, the ship is required to achieve speed or economic fuel consumption. Structure is also quantifiable in that material limits should not be exceeded though the encountered loading is more difficult to determine. Motions are more subjective but acceptable standards can be aimed for. Manoeuvring is less easy to put into a quantifiable assessment.

A general requirement for a vessel is that it can maintain a good course at sea without too much activity of the control systems to maintain it on the prescribed heading. This requirement exists not simply for calm water but in the general encounter conditions at sea which include rough water and the affects of wind. Therefore it is not only the hydrodynamic properties of the vessel but also the aerodynamic properties of the above water structure which should be covered in the design.

Another general requirement for a vessel is that of course changing. The vessel should be able to be turned by means of the control system, usually in the form of a rudder, in such a way that there is control both of the rate of turn and of the spatial envelope occupied by the vessel in a turn.

As well as the general handling qualities of the vessel when in open water there are also the handling qualities required for the vessel when entering and manoeuvring within harbour and restricted waters. In recent years these characteristics have taken on more importance in the specification of ships handling qualities. There is both the general safety of the vessel itself and the ability of pilots to handle it when bringing it in to harbour. In this very general terminology what we are seeking is to design a sound vessel with good easy course keeping, good control on the turn and responsive handling qualities in restricted waters. The greatest difficulty is in specifying what is meant by the term ‘good’.

Some vessels have requirements for special handling qualities either in the open sea or in restricted waters. Such vessels include diving support, mine hunting and cable laying ships. There are also a number of vessels, particularly ferries, which have to be able to manoeuvre rapidly in the harbours from which they operate which imposes special handling considerations (figure 2). For underwater vehicles there are the additional requirements for controlling in the vertical plane which may lead to specifications on controllability to ensure safety, particularly at high speed. Such specific requirements do have the advantage of quantification which the general characteristics lack.

The designer needs tools to be able to evaluate the performance of the vessel against such requirements. Although there is no reliable initial estimating method, several methods exist by which this subject can be addressed.

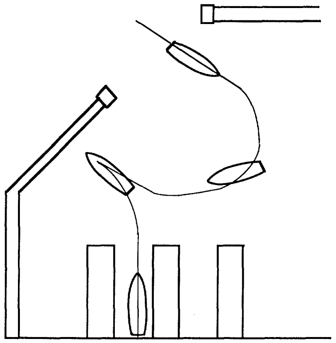

Figure 2. Typical harbour manoeuvre.

Figure 3

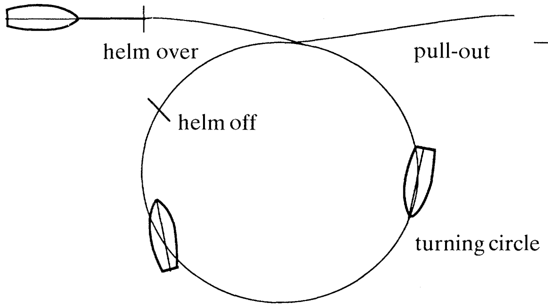

Figure 3. Free model/ship standard manoeuvre.

Figure 4

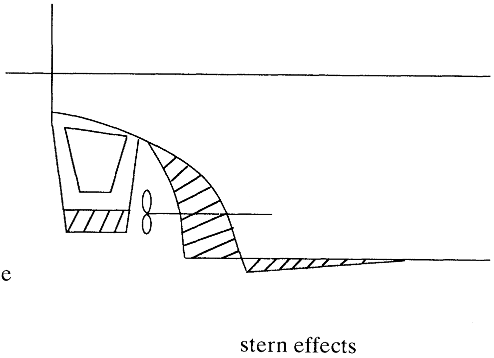

Figure 4. Changes in stern configuration to correct instability.

3. Free model tests

The free manoeuvring model is a well-established technique used in most tank testing establishments to assess the control characteristics of new designs. A number of standard test manoeuvres have been established for models and these can also be conducted on the full-scale vessel on trials (figure 3). For the most part, free model testing is conducted in either calm water basins or lakes though in some establishments it is possible to generate waves and consider the ships behaviour in various sea states. It is more difficult to simulate the affects of wind and tide though there are some specialist facilities in which this is a possibility.

The testing of scale models remains the best way of confirming manoeuvring characteristics and stability in new designs. In some ways it remains the only way of guaranteeing the performance of the vessel before sea trials, by which time it is too late to change. In this sense, model testing is essentially the prototype testing for the design. However, one of the problems with free model testing is that in general it must be confined to certain standard manoeuvres and cannot readily reproduce all possible manoeuvres that may be required of the vessel. In some instances it is possible to lay out the harbour or channel conditions in which the ship has to manoeuvre and test these at model scale but this increases the difficulty and the cost of such an approach to the solution of the problem.

It is difficult to analyse free model manoeuvres to provide information on other more complicated manoeuvres. Hence little in the way of future prediction of behaviour can be accomplished. The results of model tests also do not readily provide information on the effects of design changes. Essentially it is necessary to test the model out as originally envisaged and if its performance is not considered adequate then change the configuration and retest.

I would certainly advocate that, for any new design, scale model manoeuvring tests should be conducted. However, it is difficult to prepare a model and conduct tests in time to influence the design which is probably already heavily committed and allows little scope other than minor changes to appendages. All too frequently manoeuvring tests at model scale are scheduled late in the test programme. There are distinct advantages in preparing a model for manoeuvring tests as early as possible in the design stage even if the details of the form are not finalized and may be modified by later tests.

Apart from direct information on the testing of a specific design, free model tests are a source of some information that might be used in the preliminary design phase.

However, there has been a relatively limited amount of reported testing and evaluation of models particularly in comparison with full-scale results. The notable exceptions are the extensive tests on Esso Osaka and the early work on Series 60.

In the consideration of estimating methods, one of the essential assumptions in the use of free models is that the results can be scaled to the full-size vessel using dynamic scaling laws. For the most part they ignore any viscous or Reynolds number effects on the behaviour of the vessel. Comparisons between the model results and full-scale tests of the same hull shape have confirmed that this very broad assumption is reasonable. However, there have been some examples particularly with very full form tanker hulls where such a correspondence between model and full-scale breaks down and if the model is of too small a scale then such effects may influence the results compared with the full-scale vessel. Although this is the experience of testing, it is very hard to see how most of the essential forces on a manoeuvring vessel can arise without the existence of viscous effects in the fluid.

Free model tests also indicate that the effects of small changes are not easily predictable. The most consistent change that can be made is that of running trim. Ships and models appear quite consistent in that trim by the bow reduces directional stability while trim by the stern increases stability.

Other changes in configuration are less predictable even qualitatively in their effects on control. Quite large changes in stern area can have slight effect whereas in other tests relatively small changes showed dramatic changes (figure 4). From personal experience on submarine trials it was found that vessels of the same class exhibited measurably different control characteristics. The only rational explanation was that difference in hull geometry as built altered the hydrodynamic forces and moments generated on the hull. If such second order geometric differences in hull shape do influence the control characteristics it may be very difficult to ever produce a reliable preliminary estimate method.

4. Constrained model tests

Constrained testing of scale models is also a well-established technique used by many establishments to determine the relationship between imposed motions and the forces and moments acting on the model. Standard tests consist of the oblique tow test in the ship tank or the more informative rotating arm tests in which the model is towed not only on the oblique path but on curved path at the same time

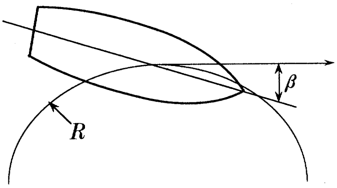

Figure 5. Rotating arm tests.

(figure 5). In some establishments use is made of the planar motion mechanism in which oscillatory motion is imposed on the model and the resultant oscillatory forces and moments relating to both acceleration and velocity can be determined. There is the same implicit assumption in such tests that, providing the model is sufficiently large, Reynolds number affects are minimal. A more important feature of the constrained model testing is that it does allow for the prediction of motions of vessels in other than standard manoeuvring tests and also provides the information necessary to design autocontrol systems for models and ships. The simulation of manoeuvres usually calls for behaviour in various propulsion states which extends the testing requirements.

The problems of the constrained model testing approach and subsequent simulation of performance is similar to that of free manoeuvring tests. It is the time required to build such models and test them related to the progress of the design programme. To some extent, providing the facilities exist, it is quicker to introduce constrained model testing, as the model is relatively simple compared with the instrumented free model. Most of constrained test instrumentation is incorporated in to fixed facilities in test tanks; however, these are expensive facilities. Perhaps the greatest problem with this approach, is that, again, it provides very little direct information to the designer in way of understanding how he can configure a hull to achieve his objective. Some attempts have been made in both free models and constrained models to identify design features by systematically changing the hull form or configuration. Thus it is possible to test models with and without rudders, bilge keels, appendages, planes, stabilizers. All of these indicate changes in manoeuvring characteristics of the vessel some marked and some not so marked. It is very difficult to identify exactly the effect of an appendage as it is not simply the effect of the appendage itself but its interaction with the main body of the hull.

There is relatively limited information published and available on such tests to help the designer. Some years ago model tests were conducted in which the hull was cut into sections and the forces measured along the different parts of the hull, the results of this work were published by Clarke (1972) together with an attempt at analysis of the forces on the body. However, both the experiments and the analysis showed that most of the problems arise with complications at the stern of the vessel. In figure 6 the measured side forces for different angles of drift have been plotted along the length of the ship. The forces and moments have been plotted as cumulative towards the stern. It can be seen that over the forward two thirds of the hull there are consistent changes with drift angle, in fact almost linear; however, towards the stern the results show marked changes for different drift angles.

Another feature of existing constrained model techniques is that they only indirectly contribute to the knowledge of the control response of the vessel. Essentially, in system terms, they provide a measure of the separate transfer

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

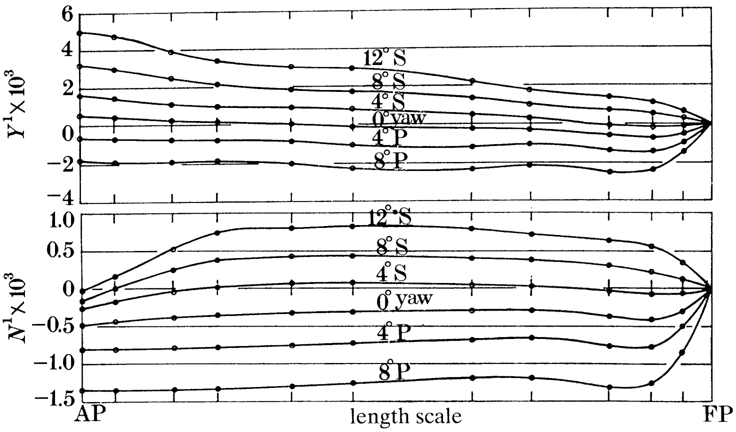

Figure 6. Fore and moment measurements on segmented model.

functions within the system (figure 7*a*). If all the motion/force transfer functions can be evaluated then it is possible to build a model of the total system. It is only then that the response characteristics of the vessel can be determined. However, by constraining the model to a single degree of freedom it becomes difficult to determine any cross-coupling effects which may exist. For example, roll which will alter the underwater geometric configuration may well couple with sway motions and forces.

In the light of these considerations some research is in hand at University College London to investigate alternative methods of testing. These could best be described as partly constrained tests in which the model has almost complete freedom to respond to an imposed control constraining force (figure 7*b*). Preliminary investigations would indicate that it is possible to deduce the free response characteristics of the model directly. It offers the possibility of experimentally relating hull configuration to control response.

5. Mathematical representation of fluid forces

The basis for the analysis of constrained model testing and for the simulation of ship manoeuvres is that of a set of equations of motions appropriate to the manoeuvring situation which are soundly derived from the laws of mechanics both dynamic and kinematic. Typically the side force equation takes the form:

$$(m+m_y)\,\dot{v}+(m+m_x)\,r = Y_{\mathrm{H}}+Y_{\mathrm{P}}+Y_{\mathrm{C}}+Y_{\mathrm{E}}.$$

It is the difficulty of representing the fluid dynamic forces, such as Y_{H} which poses the most problems in such equations. Over several years the basis for such a representation of fluid forces has been the so-called derivative theory. This originated in aerodynamics but has been successfully adapted to ship work originally by Abkowitz (1964) and by Norrbin (1960) and many other experimentalists and analysts since that time. Essentially these methods treat the hydrodynamic forces as perturbation forces arising from deviations from a baseline motion, usually straight path at constant speed. The fluid forces and moments that arise due to these perturbations can be expanded by means of a Taylor or MacLaurin series in which the changes of forces can be related to the motion variables:

$$Y'_{\mathrm{H}} = Y'_v\,v'+Y'_r\,r'+Y'_{vvv}\,v'^3+Y'_{VVr}\,v'^2r+\dots$$

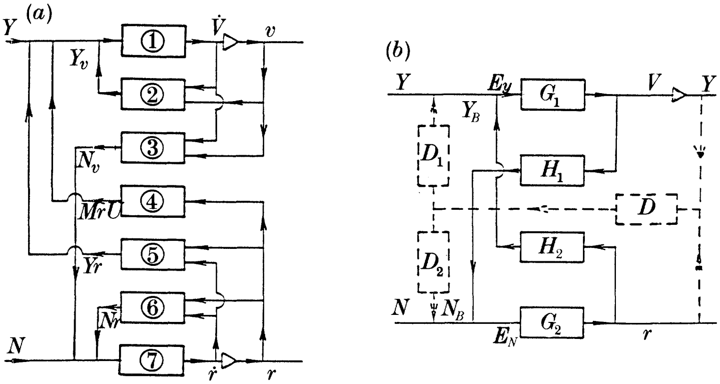

Figure 7.(*a*) System identification of surface ship in yaw and sway. (*b*) Control input to determine system response.

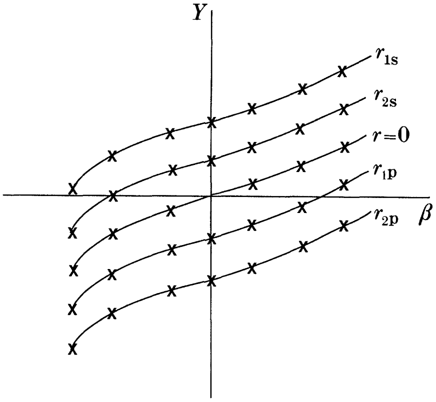

Figure 8. Typical rotating arm experiment results.

Though there are some variations in the geometric and kinematic baselines used in such representations virtually all experimenters and analysts use the same type of approach and agree in terms of the formulation of the linear derivatives of the motion. There is, however, some tendency because of the notion of a mathematical derivative to consider that the values so obtained are absolute, whereas in practice such values are essentially coefficients derived from the particular experiment and not necessarily the same as those derived in a different manoeuvre. Considerably more differences arise in describing the hydrodynamic forces on the vessel large motion. Here the linear derivative terms are insufficient to describe the hydrodynamic forces and additional terms due to both cross-coupling between motions and higher-order terms of the motion are necessary. There are quite a number of variations in the formulations and in the number of terms considered necessary to either analyse the experiments efficiently or to accurately predict the motions of the vessel in a simulation. It is considered essential to recognize that such evaluations are perfectly valid within the context of experiments from which they were derived (figure 8) and can be considered to be the best mathematical fit to that set of data but that they should not be considered as absolute values and therefore some care must be exercised in using them in any other form of manoeuvre or particularly in a situation involving extrapolation.

An essential feature of the derivative approach to representing hydrodynamic forces is that it assumes that the forces and moments acting on hull are instantaneously related to the motion at that time. However, it can be physically demonstrated and shown by analysis that the forces acting on the hull are the result of the history of previous motion. This is the so-called memory effect of fluid forces. To encompass this in a mathematical expression it is necessary to replace the derivative notation with convolution integral representation:

$$\text{derivative} \quad Y(t) = Y_v\, v(t) + Y_{\dot{v}}\, \dot{v}(t),$$

$$Y_v(t) = \int_{-\infty}^{0} h_v(\tau)\, v(t-\tau)\, \mathrm{d}\tau.$$

This considerably complicates the representation of the forces on a body for linear assumptions and even more so if nonlinear effects are to be included. A considerable body of evidence indicates that, at full scale, the memory effect is of small consequence to the prediction of the motions of the vessel. While accepting therefore that this additional complication need not be introduced into full-scale manoeuvring predictions, some care must be exercised in the analysis of the model tests where the rate of change of motion or the frequency content of imposed motion may be such that memory effects do change the results of the measurements.

An alternative representation of vessel manoeuvring was provided by Nomoto (1957). He showed that the second-order equation of motion in sway and yaw could be replaced by a first-order equation characterized by two terms K and T. K is essentially a rudder effectiveness term while T is a time response characteristic of the vessel. The results of zigzag manoeuvres on ship trials are amenable to an analysis based on this method.

It can be shown from linear, steady-state analysis that the turning response due to rudder input takes the form

$$r/\delta = (Y'_\delta/Y'_r)\,(l_\delta - l_v)/(l_r - l_v).$$

Not only are the rudder force derivative and the yaw force derivative of the ship required but the difference between the location of the rudder and the hydrodynamic centre of sway force is an important factor and even more important is the denominator. It can be shown that this denominator term which is a combination of moment and force derivatives in sway and yaw, can be considered as a difference between the centre of action of hydrodynamic sway forces and the centre of action of forces due to rotation. This has been better described by Norrbin (1987) in the terms $(l_r - l_v)$. This term appears in the general equations of motion as the stability discriminate of such a system. Basically it says that if the centre of action of rotational forces is ahead of the centre of action of sway forces then a vessel will be stable and tend towards straight-line motion. If it approaches zero then the vessel becomes marginally stable and if negative, the vessel will be unstable and tend to sheer from a straight course. In the near zero situation small deflections of the rudder can result in large rates of turn of the vessel. In the negative condition it is possible to have a 'loop' in the Dieudonné spiral in which inverse action of the rudder takes place and jump phenomena occur in steering the vessel from port to starboard.

In terms of preliminary design assessment, the K and T formulation for surface ships has attractions particularly if these response characteristics can be related to variations in hull and appendage configuration. Some published work exists for certain ship types which provides a means of selecting rudder size (Nomoto *et al.* 1957; Norrbin 1987).

6. Motion prediction and simulation

There is considerable literature relating to various simulation models that have been derived and built up by investigators. For the most part such investigators have applied validation techniques to the simulation model comparing either with full scale or model tests that give assurance that their simulation is reasonably accurate. It is the consideration of the author that this is probably the best state of the art in manoeuvring in that such models are reasonably sound and reliable and useful for their purposes of either predicting motions of vessels or in providing simulations for autopilot and for crew training.

The main problem with such models is the representation of the hydrodynamic forces in the equations. The majority of models adopt the derivative approach using linear, non-linear and cross-coupling terms.

Where a considerable library of past model tests results is available it is possible that a reasonable approximation to the ship can be interpolated from such results. Any methodical variation series of tests will considerably assist in selecting appropriate input data. However, it should be recognized that such data can only be regarded as typical inputs to the simulation model and are not specific to the design in hand.

7. Direct computation methods

The third category of techniques available are those of the numerical or computational method based solely on the geometric knowledge of the hull form. The attraction of such methods is that they could be used at the early design stage in the vehicle.

At the early stages of design, the hull form and its appendages are ill defined and usually the only information available are the major geometric factors such as length, beam, draught and some form parameters. Some formulations based on such information are available for hydrodynamic derivatives both of velocity and acceleration. In 1981 Inoue *et al.* (1982) provided information on estimates of derivatives in terms of hull parameters:

$$\text{sway derivatives}\quad \begin{cases} Y'_v = [a_1 K + f(C_B B/L)](1+b_1\tau'), \\ N'_v = a_3 K(1+b_1\tau'), \end{cases}$$

$$\text{yaw derivatives}\quad \begin{cases} Y'_r = a_2 K(1+b_2\tau'), \\ N'_r = (a_4 K + a_5 K^2)(1+b_4\tau'), \end{cases}$$

where K is a draft to length aspect ratio, τ' in a trim to draft ratio, and a, b are constants derived from database.

Similarly nonlinear terms can be estimated from charts as functions of hull dimensions. Clarke *et al.* (1983) published another series of formulations based on the regression analysis of a number of vessels of the same type:

$$Y'_v = 0.00102 - 2.3(T/L)^2 - 1.466C_B(B/L)(T/L),$$
$$N'_v = 0.0008 - 1.758(T/L)^2 + 0.00768C_B(T/B).$$

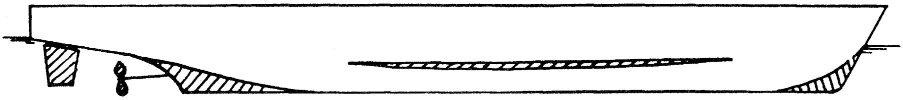

Figure 9. Appendage elements treated as low aspect foils.

Such formulations can prove very useful in estimating the hydrodynamic forces of a ship in manoeuvring and thence simulating or predicting the motions of a ship in given circumstances. It should be recognized, however, that such estimates can only provide what could be termed 'the expected values for the type of ship'. There can be no guarantee that any specific vessel design will have values exactly according to these formulations. It is to be noted that in the Inoue formulations, the trim of the vessel is included, whereas it is not in the Clarke formulations.

If estimates are made of individual derivatives using approximate formula derived from regression analysis and then these are combined into the terms necessary to identify centres of action and stability discriminates, then there is a possibility of large errors occurring in the initial estimates of the manoeuvring characteristics of the design. However, the degree of success achieved by validated simulations suggests that this is not such a great problem as it would appear and there may well be some form of self-correction mechanism at work within the calculation. However, from a design point of view it would be highly desirable if estimate and formulations were configured to provide these important manoeuvring characteristic terms rather than the indirect values of derivatives. It is possible to visualize why length/draught, draught/beam and block coefficient would be significant features in dictating the side force generated by a vessel in sway motion, but it is less easy to see why these parameters by themselves affect the centre of action of such a force. It would seem that some parameters associated with the distribution of shape along the length should be included in such formulations.

8. Low aspect foil approaches

Somewhat later in the design process with more information on the hull form and a proposed location, sizing and alignment of appendages the designer would hope for a more detailed analysis technique for the manoeuvring qualities.

Such methods do exist and have been derived from aerodynamic work. Such methods were pioneered by Jacobs (1966), in treating the ship as its component parts, i.e. as a bare hull plus appendages (figure 9) using lifting surface theories. The aircraft analogy is well described in Hoerner (1975). With an aircraft, the forces are dominated by major lifting surfaces of wings and planes with the hull playing a minor part, whereas for a ship the hull forces dominate and the appendages are relatively small and of low aspect ratio. Such methods are very attractive from a design view point, as they deal with the ship in terms of the components over which there is some influence in the design phase. The main problem with such methods are in dealing with the interference effects between isolated components attached to the hull. For the most part such prediction methods apply to small deviations from a straight path and less information is derived from these approaches for large motion manoeuvres.

There is an approach which has been successfully used in seakeeping and might be expected to be also successful in manoeuvring. This is the strip calculation, considering the flow across individual transverse sections and summing across the whole of the vessel to determine the centres of actions of the forces. In the paper by Clarke (1972) he showed that such an approach can be reasonably successful on the fore body of a ship but unfortunately seems to fail at the stern. The segmented model tests mentioned in §4 also indicated this nonlinear behaviour of forces at the stern of the vessel. It might be deduced, that such effects are due to what might be called a 'wake shadow' due to the changes of flow over the fore part of the ship affecting the direction of the flow at the stern of the vessel. Proper allowance for upstream effects on downstream sections is a desirable feature of such an analysis.

An essentially strip method approach has been used with some success by Lloyd (1983) on underwater craft making an allowance for the vortex shedding from forward appendages on the stern appendages and hull. One important step in this is that it is necessary to make estimates or use empirical data for the path of such vortex lines and sheets that are shed on the hull. It is relatively easy to locate the origin of such vortex lines and sheets on the truly lifting surfaces or appendages but extremely difficult to identify the origin of the shed vorticity from the hull. Indications are that this is dependent on second-order or detail features of the hull and can differ between ships of the same class or of very similar hull form.

9. Computer fluid dynamic approaches

Over the past decade or more, considerable advances have been made in the direct calculation of fluid velocities and pressures over a moving body using what is generally known as computer fluid dynamics. This has been made possible by the increase in computer power available to most design offices.

The techniques applied to ship problems have, in general, been initiated in aerospace industry or related to offshore structures. Adaptions are possible from both sources to the ship motion problem. Considerable progress has been made in the prediction of ship motions in waves, progress is also being made in the prediction of ship wavemaking resistance and a number of attempts have been directed on the ship manoeuvring problem many associated with lateral forces on sailing vessels but there appears to be some way to go before a method will be readily available to designers.

An almost bewildering variety of techniques have been put forward for fluid computational methods. One group are those that seek to solve the governing fluid equations throughout the volume of fluid surrounding the hull as well as satisfying the boundary conditions at the hull due to its motions. The computation may run to many thousands of node points. In many cases a specially formulated grid is generated to solve the particular problem. The method of solution which may be by finite difference equations or by a variety of finite-element formulations. For manoeuvring the behaviour in the general volume of the fluid is of less interest except in situations of interaction between hulls or if the computations are to include the effects of confined waters.

Another group of computational methods, which would seem more appropriate to manoeuvring are those associated with boundary-element formulations. The most generally applied technique is the panel method usually considered to originate from the work of Hess & Smith (1967).

Again a wide variety of techniques are used to solve particular problems. Adopting a choice of subdivision of hull surface and a choice of singularities. Faced with such variants it is difficult to assess which will lead to methods most suitable for the design evaluation of manoeuvring characteristics of a new ship design.

The problems to be overcome do not cease at this stage. Many hydrodynamic problems can be solved in the frequency domain using Fourier transform techniques, however, manoeuvring requires solutions in the time domain. Time domain solutions considerably increase the requirement for computational power and speed. It also introduces problems in the significance of the initial conditions from which the computation is commenced. It is possible that in many situations the transient time during which initial conditions still effect the solution will be of considerable length and may encompass the total time of the manoeuvre under consideration. This is of considerable practical interest as, for many real manoeuvres, the steady-state condition is never reached.

However, the more difficult aspect to overcome is the actual modelling of fluid behaviour for manoeuvring problems. Most of the techniques described are based on inviscid formulations of fluid equations. For the most part it would appear that the manoeuvring problem can be approached as a high Reynolds number condition in which assumptions of a thin boundary layer on the hull are permissible. The inclusion of viscous effects can be included by invoking approximate boundary layer calculations from the initial inviscid flow computations (Gadd 1971) or by approximate Navier–Stokes solvers. Appendages and control surfaces with an identifiable trailing edge enable some assumptions to be made on the origin of vortex lines or sheets and assumptions or computations made on their location downstream where the potential jump can be assumed to exist in an inviscid computation. The primary problem remains with the main hull where it is extremely difficult to assess where separation or vortex shedding will occur.

Although it remains a hope that these computational methods may be developed to a stage where they can be deployed in design, it must remain questionable as to whether they will provide the insight required for a designer to successfully modify his design to improve its performance. The anomolous feature is the depth and complexity of the computations which appears inconsistent with the requirement of design, at least in the initial stages, of broad assurance that reasonable choices of configuration have been made.

10. Conclusions

Despite considerable work and efforts by many researchers over the past two decades the situation remains that the ship designer has only limited guidance by which to control the manoeuvring characteristics of a new vessel at the early design phase. The analysis of existing ships and model tests provides a measure of expected performance based on form parameters but cannot be seen to be a guarantee of the performance of a specific hull form. If the design calls for specific conditions of manoeuvring performance then the main recourse of the design is to have model tests conducted as early as possible; at best concurrent with resistance and propulsion tests if not before.

The calculation methods based on build up of bare hull and its appendages appears to be the most useful guidance to the designer. Even where such methods may be incorrect in absolute terms, they very often provide good guidance on the effect of small changes.

The general dynamic modelling of ships and simulations appear to be in a well-developed and useful state provided reliable data on the hydrodynamic forces or derivatives can be obtained. Regression analysis derivatives are useful for predicting the expected behaviour of a ship but, for specific design performance, constrained model testing is the primary source of derivative data for ships. For both estimated and measured model testing more emphasis should be placed on the direct evaluation of the parameters that govern behaviour, i.e. the location of hydrodynamic centres of action both in small and large perturbations from straight-line motion.

Computational methods based on more detailed hull definition are beginning to emerge and it is hoped that the time will come when these are in a form that can be used in the design phase. However, the manoeuvring ship is probably the most difficult that exists in fluid dynamics. There is a rather strange disparity between the imprecision of manoeuvring and control requirements of ships and the complexity of the fluid dynamics required for their solution.

References

Abkowitz, M. A. 1964 Lectures on ship hydrodynamics – steering and manoeuvrability. Hydro-og Aerodynamisk Laboratorium, Lyng-by, Denmark, *Rep. no.* Hy-5.

Asinovsky, V. & Hagen, G. R. 1987 Ship manoeuvrability analysis using the differential approach. *Trans. Int. Conf. Ship Manoeuvrability*, pap. 9, vol. 1.

Clarke, D. 1972 A two dimensional strip method for surface ship hull derivatives. *Int. Symp. Directional Stability and Control*. London: IME.

Clarke, D., Gedling, P. & Hin, G. 1983 The application of manoeuvring criteria in hull design using linear theory. *Trans. RINA* **125**, 45–68.

Gadd, G. E. 1971 The approximate calculation of turbulent boundary layer development on ship hulls. *Trans. RINA* **113**, 59–71.

Gadd, G. E. 1985 A calculation method for forces on ships at small angles of yaw. *Trans. RINA* **127**, 257–268.

Hamamoto, M. 1985 Lift acting on slender body and its flow model. *J. Kansai Soc. nav. Architects, Japan*, no. 196.

Hess, J. L. & Smith, A. M. O. 1967 *Prog. aeronaut. Sci.* **8**, 22–44.

Hirano, M. 1980 On calculation method of ship manoeuvring motion at initial design stage (in Japanese). *J. Soc. nav. Architects Japan* **147**, 144–153.

Hoerner, S. F. 1975 *Fluid-dynamic lift*. New Jersey: Hoerner Fluid Dynamics.

Inoue, S., Hirano, M. & Kijima, K. 1981 Hydrodynamic derivatives on ship manoeuvring. *Int. Shipbuilding Prog.* **28**, 112.

International Maritime Organization (IMO) 1985 Interim guidelines for estimating manoeuvring performance in ship design. IMO Document MSC/Circ. 389.

Jacobs, W. R. 1964 Estimation of stability derivatives and indices of various ship forms and comparison with experimental results. Davidson Laboratory, Report 1035, New Jersey.

Lloyd, A. R. S. M. 1983 Progress towards a rational method of predicting submarine manoeuvres. *RINA Int. Symp. Naval Submarines*. London.

Nomoto, K., Taguchi, T., Honda, K. & Hirano, S. 1957 On the steering qualities of ships. *Int. Shipbuilding Prog.* **4**, 354–370.

Norrbin, N. H. 1960 A study of course keeping and manoeuvring performance. *SSPA Rep. no.* 45.

Norrbin, N. H. 1987 Some notes on the rudder derivatives and the representation of the control force in the prediction of ship manoeuvring capabilities. *Int. Conf. Ship Manoeuvrability*, pap. no. 14, vol. 11.

Price, W. G. & Mingyi Tan 1987 A preliminary investigation into the forces acting on submerged body appendages. *Int. Conf. Ship Manoeuvrability*, pap. no. 13, vol. 11.

Yamasaki, K. & Fujino, M. 1984 Hydrodynamic forces acting on the three dimensional body advancing in the free surface. II, III (in Japanese). *J. Soc. nav. Architects Japan* **156**, 163–170; **157**, 229–243.

Discussion

G. VICTORY (*Surrey, U.K.*). Professor Burcher apparently accepts that manoeuvring characteristics of vessels are difficult, if not impossible, to predict in the design stage, and generally must wait for manoeuvring trials after completion of the vessel. He does indicate some of the ways in which poor characteristics can be improved and I would enquire whether he would suggest ways by which the steering characteristics of VLCC's could be improved, particularly when the engines are put astern while the ship has forward motion. In examining a number of cases at IMO, some years ago, it would appear that most VLCC's were partly unstable in ahead motion and uncontrollable if the engines are put astern. The subsequent path of the vessel could be anywhere within a spade-shaped area up to 5 miles ahead and a mile wide. If there is sea room one technique is to turn the vessel slightly before going astern then try to maintain a straight path. However, such a manoeuvre is not appropriate in a narrow channel. Can Professor Burcher say whether there are any improvements possible to avoid a major incident?

R. K. BURCHER. Mr Victory is correct in stating that the stern rudders on most vessels become ineffective once the engines have been put astern. The subsequent trajectory of the ship is virtually unpredictable after engine reversal. If the rudder is used before engine reversal, then the spread of trajectories can be limited to port or starboard of original track but a certain indeterminacy will remain of the subsequent track. A number of devices have been investigated and reported to the ITTC Conference to overcome this problem. If fitted, a standard bow thruster can be used. Other side thruster devices involved the diversion of flow to port or starboard from a duct on the bulbous bow or a ‘one shot’ system in which a tank high in the bow was discharged via ducting below the water. In some vessels much of the braking effect from high to moderate speeds is achieved by stopping the shafts rather than reversing, a degree of steerage way can then be maintained by the rudder until the speed has fallen off at which time the engines must be put astern to stop the vessel.

J. E. FFOWCS WILLIAMS (*University of Cambridge, U.K.*). I was interested in Professor Burcher's observations that very slight geometrical differences sometimes seem to have great influence on the manoeuvring characteristics of vessels, and am reflecting on the potential flow modelling of ship loads. In a manoeuvre there will be sustained yaw involving a cross flow which will wash away the streamwise boundary layer, possibly causing separation of the transverse flow and setting up strong secondary flows, with streamwise vorticity that is not negligible. Does he have any feeling for the importance of that effect and have you any comments on the validity range of potential modelling?

R. K. BURCHER. I fully agree that in large yaw or sway motion it is to be expected that the cross flow will modify or even carry away the streamwise boundary layer. This can lead to separation and shed vorticity. If this passes near the stern of the vessel then the fluid forces on the rudder and skegs will be considerably different to that using a simple potential theory even if a boundary layer computation is included. In a tight turn, however, such shedding effects will be carried well clear of the stern and may have little effect. It is therefore possible that potential modelling can be more successful for large motions than when applied to the small perturbation motions usually assumed in theoretical analysis.