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Contributions to the understanding of Ship Powering, Ship Rudders, Ship Design and Marine Current Turbines

by

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Contents

1. Introduction

1.1 General

This Thesis is based on original research carried out by the writer and published between 1978 and 2017.

The research has focused on developing a better understanding of ship hydrodynamics in the areas of ship resistance and propulsion, ship motions and rudders/manoeuvring, together with their effective integration and applications in the fields of ship design and operation. Fundamental research has also been carried out into the performance of marine current turbines, applying technology transfer from marine propellers and wind turbines.

Physical experiments have played a significant role in the research and an important output has been the generation of high quality experimental data which help explain the fundamental physics, provide benchmark data at a detailed level for validating theoretical and numerical techniques and data for practical design purposes. This approach has entailed the development of innovative testing techniques involving new test rigs together with new data measurement and acquisition methods.

1.2 Research areas

Work of significant importance and contributing to original research and the advancement of knowledge can be grouped under four main research themes:

(i) The Components of Ship Resistance.
This has entailed the development of a fundamental understanding of the components of resistance of high speed commercial catamarans and monohulls in order to improve power prediction methods.

(ii) Ship Rudders and Rudder-propeller Interactions.
This has entailed the development of a fundamental understanding of the operation of marine rudders including, in particular, their performance downstream of a propeller and hull.

(iii) Ship Design.
The development of new design synthesis and concept exploration techniques for high speed semi-displacement commercial catamarans and monohulls.

(iv) Marine Current Turbines (MCTs).

This work was the result of an application of technology transfer, using the writer's existing expertise in the design of marine propellers. The investigations included carrying out detailed tests on models of MCTs in order to provide a fundamental understanding of their operation, including performance characteristics and cavitation inception.

1.3 Dissemination of Research

Publication of the research has been widely received in national and international academic communities. Dissemination of the research has been through Journal Publications, Departmental Working Papers and presentation of papers at Conferences and meetings worldwide. These Conferences and meetings were held in the UK, Australia, Austria, China, Germany, Greece, Holland, Indonesia, Italy, Japan, S. Korea, Norway, Russia, Spain, Sweden and USA.

1.4 References

Selected papers referred to in the text are listed at the back of the thesis. The ten most significant publications are marked with an asterisk (*) and copies of these are included in the back of the thesis. Supplementary papers such as Southampton Ship Science Reports (Departmental Working Papers) are listed in Appendix 2. The University of Southampton Ship Science Reports referred to in the Papers in the thesis can be obtained without cost from: www.eprints.soton.ac.uk.

Personal contributions by A.F. Molland to each paper, together with co-authors, are shown after the Reference list. The contribution to each paper by A.F. Molland is shown as a percentage, made up of supervision of the research, estimate of share of the work and contributions to the writing of the paper.

2. Components of Ship Resistance

2.1 Introduction

Much of the research in this area has concentrated on the calm water resistance components of high speed semi-displacement monohulls and multihulls and, in particular, high speed semi - displacement commercial catamarans. The commercial applications of high speed catamarans increased significantly in the early 1990s. Little information was, however, available for carrying out reliable powering estimates for such vessels, particularly in the higher speed range. There was a need to establish and understand the components of resistance for these vessels in order to carry out correctly the powering process which, in the main, involves extrapolating model resistance data to full scale.

A research programme was initiated by the writer which, over several years, entailed fundamental and thorough investigations to identify and quantify all the possible components of resistance of commercial catamarans and the influence of hull separation on the individual components. These investigations were carried out by Postgraduates and Research Assistants under the supervision of the writer. The results of the investigations are given and discussed in [1] to [10]. The programme of work started with an extensive range of model experiments on a series of catamaran hulls, based on the NPL hull form, with systematic changes in length-displacement ratio and hull separation, [1], [2]. The experiments included towing tank measurements of the total resistance, total viscous resistance and wave pattern resistance. These results for a systematic series of ten models provide an insight into the hull resistance of such vessels and data suitable for design purposes. These were the first published results to provide systematic and fundamental data for higher speed catamarans. They still represent the widest available data set for round bilge commercial catamarans and are internationally accepted for benchmarking and design purposes, [1] and [2].

Further routine tests were carried out for change in prismatic coefficient, [3].

Detailed experiments in a wind tunnel examined in more depth viscous resistance interaction between catamaran hulls, for changes in hull separation, [4], [5].

Experiments were also carried out to examine the likely levels of induced drag on catamaran hulls, [7].

2.2 Measurement and Derivation of Resistance Components

2.2.1 Resistance Components Examined in the Course of the Research programme.

a) Friction

b) Viscous pressure, plus viscous interference in the case of catamarans

c) Wave pattern resistance: Total wave resistance might also include wave breaking, plus wave resistance interference in the case of catamarans

d) Induced drag due to crossflow over the hulls of catamarans

e) Transom effects/drag

f) Air drag

2.2.2 Measurement Techniques Used in the Derivation of the Resistance Components

a) Measurement of total resistance using a dynamometer

b) Direct physical measurement of total viscous resistance from wake traverse experiments

c) Direct physical measurement of wave pattern resistance using wave probes

d) Wind tunnel tests on catamaran hulls and a pair of ellipsoids

e) Induced drag due to crossflow over hulls: measurements of sideforce and lift, hence induced drag on hulls

All these techniques were used in the course of the research programme and are described in [1] to [7].

2.2.3 Form factor

As part of the estimation of the components of hull resistance and the model to ship extrapolation process, it is necessary to identify total viscous resistance, which includes the need to identify suitable form factors, Equation (2.1):

$$C_T = (1 + k)C_F + C_W \qquad (2.1)$$

where C_T is total resistance coefficient, $(1 + k)$ is the form factor, C_F is the friction resistance coefficient, $(1 + k)C_F$ is the total viscous resistance and C_W is the wave resistance coefficient.

The notation developed for catamarans is described in Appendix 1.

The following detailed experimental methods were used to derive the form factor:

(i) Form factor from total viscous resistance divided by friction resistance
(ii) Form factor from total resistance minus wave resistance divided by friction
(iii) Form factor from slow speed tests when wave resistance tends to zero and form factor from total divided by friction, or the approach of Prohaska which uses a regression of the low speed data
(iv) Slow speed tests repeated with bow down/stern emerged

The wake traverse experiments were also able to identify any surface debris due to wave breaking between and outside the hulls. Removal of debris would effectively decrease the viscous resistance and form factor.

In order to gain a deeper insight into catamaran viscous resistance, viscous interactions between the hulls and form factors, detailed force and pressure measurements were carried out on a pair of ellipsoids in a wind tunnel, together with numerical investigation using a commercial RANs package, [4] and [5]. This work has provided further fundamental evidence on the likely levels of viscous interference and form factor for multihull vessels.

Form factors derived from wake traverse experiments and total resistance minus wave resistance were considered to be higher than expected. Possible reasons for such relatively high form factor values were examined in some detail and possible corrections considered. Some final conclusions are discussed in [6], where lower form factor values are proposed for practical use. This paper results from consultation, communication and collaboration between Southampton and Australian research programmes.

2.2.4 Catamaran Induced Drag

In order finally to identify all the components of hull resistance, an investigation was carried out to examine the likely magnitude of any induced drag. The presence of induced drag would effectively reduce the form factors already derived and discussed. A catamaran comprises two demihulls and although the flow about the catamaran centreline is symmetric, the flow about the centrelines of the individual hulls is not. The asymmetric nature of the fluid crossflow around the demihulls causes sideforces and hence induced drag to be experienced on the demihulls. The sideforces generated by each demihull act in opposition and cancel whereas the induced drag of both demihulls act together to resist the forward motion of the vessel. A detailed experimental investigation was carried out to determine the likely magnitude of the induced drag, and the procedure and results of the tests are described in [7]. Whilst the sideforce was reasonably large at 4% to 16% of monohull resistance, the induced drag was less than 0.3% of the monohull resistance and, for practical purposes, can be ignored.

2.2.5 Superstructure Drag

In support of the investigations into hull resistance, and to complete the resistance components, experimental and numerical investigations were carried out in two wind tunnels into the superstructure drag of high speed commercial catamarans, [8]. Such data are also applicable to most passenger ships. The relatively large superstructures of ferries and passenger ships can create a significant drag augment, and essential quantitative information was required for this component. The detailed investigations included measurements of drag, flow observations and CFD (2D) studies, for a range of representative superstructure shapes.

2.2.6 Flow over Ship Superstructures

Related to the drag of superstructures is the actual flow over the superstructure and the influence of the superstructure on wind speed measurements. Experimental and numerical investigations were carried out to determine the influence of the superstructure on the measurement of ocean wind speeds and the level of flow distortion. The work was carried out by a postgraduate under the writer's supervision, in conjunction with the National Oceanography Centre (Southampton), in order to determine suitable corrections to sensor measurements on Voluntary Observing Ships (VOS). The results are also useful for correcting any wind speed measurements on ships including, for example, measurements during sea trials. The investigations entailed flow observations and PIV measurements in a wind tunnel for typical commercial ships and the application of CFD techniques, [9], [10], [11]. Flow patterns above the bridge were obtained for representative ships. Normalised wind speeds were obtained leading to proposed corrections for wind speed bias above the bridge. The writer was not involved with much of the early work discussed in [10], but this reference has been included as a link between [9] and [11].

2.2.7 Numerical Wave Resistance

Over the same period as the experimental investigations, work took place on the development of thin ship theory to estimate the wave pattern resistance of higher speed semi-displacement monohulls and catamarans. This proved successful and included the important development, under the supervision of the writer, of the virtual stern to estimate transom effects, [12]. These theoretical techniques have also been successfully adapted for the prediction of ship wave wash, discussed later.

2.3 Wave Wash

Wash can be seen as a by-product or extension of the wave resistance investigations. The wash generated by high speed vessels, often operating in relatively shallow water, can have a significant impact on safety and the environment. A research programme under the writer's supervision, investigated the generation of wash from fast vessels. The programme was carried out in collaboration with researchers at Queens University, Belfast who investigated the propagation of the wash waves and Portsmouth University who investigated the impact of the wash on the environment. The work was EPSRC/Industry funded and entailed fundamental experimental and theoretical investigations into the generation of wash, [13], [14], [15].

Molland *et al.* [13] give a background to basic thin ship theory, together with necessary modifications to the basic theory, including consideration of transom stern effects. Some example applications are discussed. Overall, it was found that the numerical method being developed and described can be usefully employed as a simple and effective means of estimating near field ship wash with low computational effort.

Molland *et al.* [14] describe further refinements to the basic thin ship theory to model wash, including transom stern effects and predicted hull wave profile. The theory was validated for deep water, and for shallow water using the new experimental data reported in [15].

Molland *et al.* [15] report on an extensive set of detailed resistance and wash wave measurements on high speed displacement craft in shallow water. The data derived and presented provide a detailed insight into the performance of high speed commercial monohulls and catamarans in shallow water. These data represent the first systematic tests in shallow water for vessels of this type. The data are also suitable for design and wash applications and for the validation of theoretical analyses.

2.4 Resistance Components: Summary

The experimental work, together with numerical modelling, has made significant contributions to a fundamental understanding of the resistance components of fast semi-displacement craft, particularly commercial catamarans. This has enabled more realistic predictions of propulsive power to be made for these vessel types. The work on wash provided a much deeper understanding of the origins of wash and, importantly, the means of predicting levels of wash by coastal, river and port authorities.

3. Ship Rudders and Rudder-Propeller Interactions

3.1 Introduction

Fundamental work has been carried out on rudders and rudder-propeller-hull interactions. This work has provided significant contributions to the understanding of these interactions and their role in ship manoeuvring and control.

The development of new rudder types and the need for improvements in the understanding and prediction of ship coursekeeping and manoeuvring characteristics provided the impetus and need for this work. Action was also being taken towards the introduction of international legislation concerning coursekeeping and manoeuvring requirements. Much of the work reported here was EPSRC/Industry funded and entailed extensive experimental and theoretical studies into ship rudders and propellers and their interaction. These rudder and rudder-propeller interaction investigations were carried out by Postgraduates and Research Assistants under the supervision of the writer.

Detailed experiments were carried out to examine and understand the physics of rudder operation, including measurements of forces, moments and pressure distributions, stall and flow observations of shed vortices and separation. An innovative approach to the experimental work was used which entailed testing rudders and propellers in large wind tunnels (with sections 2.0m × 1.5m and 3.5m × 2.5m) with large models and high wind speeds, enabling high Reynolds numbers to be achieved. The test rigs do not allow for free surface effects but this restriction is not likely to be significant except where a vessel is in light ballast and/or the rudder is working close to the free surface. Tests in air preclude any investigation of cavitation which is not seen as being important in these tests. Effects of compressibility are not significant provided limitations on propeller revolutions (hence blade inflow speeds) take this into account. In using such an innovative approach in wind tunnels, it was necessary to develop new test rigs, dynamometers and test techniques.

Early research concerned the free-stream characteristics of ship semi-balanced skeg rudders, a free-stream rudder being without a propeller or hull upstream, and the work formed the basis of the writer's Ph.D. [16]. The skeg rudder is a rudder type which has seen increasing use on all ship types, from ocean going sailing yachts to large super tankers and container ships. The skeg rudder has a number of attributes which include having a lower pintle located close to the centre of loading (or centre of pressure) and providing some balance to lower the steering gear torques. The skeg rudder investigations entailed identifying the separate forces on the movable rudder and fixed skeg, flow separation effects aft of the skeg, tuft studies, skeg gap effects, gap flow, sealed skeg gaps and cavitation. This work has received international recognition and the experimental results have been adopted by many researchers and designers as benchmark data for skeg rudder free-stream characteristics. However, free-stream data have some limitations noting, in particular, the need to include the effects of a propeller if situated upstream of the rudder, and how these propeller effects are suitably modelled.

The natural extension to the free-stream work was, therefore, the investigation of rudder performance when operating downstream of a propeller, [17], [18]. In this case the rudder operates in a complicated flow regime due to the flow velocities and directions induced by the propeller. The most common rudder design and performance prediction method entailed the use of free-stream characteristics for a particular rudder type with corrections for the influence of the hull and propeller. In this case the rudder in the free-stream condition and the modifying effects on the rudder of the hull and propeller are treated as individual components of the complete system. This method is known to be deficient in that it does not correctly account for the actual physical interaction between the various components. Little had been done experimentally to discover the true physical nature of the flow over rudders and the resulting forces. An underlying aim of the rudder research programme therefore was to provide a better understanding of the fundamental flow phenomena and to acquire good quality data for design and validation purposes, together with the development of improved rudder performance prediction procedures. The research would lead to an enhanced model where the rudder plus propeller is modelled as a combination in isolation. The work entailed extensive experimental investigations, which considered many rudder-propeller combinations, together with the development of theoretical and numerical methods. The experimental work was extended to include tests on rudders and propellers downstream of centreboards of different lengths and a representative hull; these tests also included the effects of the boards and hull in yawed conditions.

3.2 Discussion of Free Stream and Rudder-propeller Interaction Experiments

3.2.1 Skeg Rudders: Free Stream

The early work on rudders entailed a thorough examination of the performance characteristics of semi-balanced ship skeg rudders in a free stream, namely in the absence of a propeller or hull upstream, Goodrich and Molland [16]. The tests were carried out in the 2.0m × 1.5m wind tunnel on three rudders having taper ratios of 0.59, 0.80, 1.00, and skeg and overall characteristics that are typical for the rudders fitted to many modern ships. Further details of the rudders, test rig and procedures are described in [16]. One purpose of the investigation was to provide a better understanding of the performance of the skeg rudder when the skeg is subjected to drift angle, which results from cross flow at the stern when the ship is on a turn. In the case of the skeg rudder, drift angle leads to negative inflow angles on the skeg.

Due to the low aspect ratio of these rudders, a very strong tip vortex was developed. Similarly, at the junction of the fixed skeg and movable part, with a distinct change in pressure, a vortex was also formed, effectively similar to the vorticies shed at the ends of the flaps on aircraft wings. These vorticies were visible during tuft studies and smoke flow tests, and the effects of the vortices were clearly visible in the spanwise pressure distributions, [16].

For the skeg rudder, with increasing angle of attack, discontinuities occur in the growth of lift and drag together with a large movement of the centre of pressure. These discontinuities are due to the early separation behind the skeg, which was confirmed by visual studies. Thus an intermediate situation can exist for the skeg rudder where the flow behind the skeg is fully separated whilst that clear of the skeg is still attached. Compared with an all-movable rudder, the rate of increase of lift is considerably less for the skeg rudder, but its stall angle is delayed and its maximum lift coefficient is not much less than the all-movable rudder. However, the lift/drag ratio, or measure of efficiency, for the skeg rudder is appreciably less than the all-movable rudder. It was also recorded that the movement of the centre of pressure, both chordwise and spanwise, with increasing angle of attack is significantly larger than that for the equivalent all-movable rudder. These movements have implications for root bending moments on the rudder and torque effects on the steering gear.

3.2.2 Rudder-propeller Interactions

As discussed earlier, a basic objective of the propeller-rudder interaction investigations was to establish a fundamental understanding of the flow characteristics and the forces and moments developed on the rudder. This was achieved by measuring forces, moments and pressures on the rudder, together with flow observation studies. These tests covered a wide range of propeller-rudder combinations, each representing a schematic of actual rudder-propeller combinations found in practice. The tests included a number of rudder aspect ratios together with the influence of the longitudinal, transverse and vertical position of the rudder relative to the propeller, and the coverage of the propeller diameter relative to the rudder span. The basic results of these investigations are reported in Molland and Turnock [17] and Molland, Turnock and Smithwick [18].

The first series of experiments are reported in [17]. These experiments were carried out in the 3.5 × 2.5m wind tunnel and simulated the condition of the rudder operating aft of a propeller but without the influence of the hull. The propeller-rudder test rig is described in [17]. The propeller was modelled on a Wageningen B4.40 propeller and open water (air) tests recorded characteristics similar to published data for the B4.40 propeller. Four rudder geometries were tested, a skeg rudder and three all-movable rudders, and the longitudinal separation between the rudder and propeller was varied. Pressure measurements were made over the rudders. The tests were carried out for three propeller thrust loadings.

The experimental results provided an insight into the physics of the flow and give a better understanding of the rudder-propeller interaction problem. In particular, the spanwise load distributions, derived from the pressure measurements, indicate the effect of both axial and rotational rudder inflow velocities induced by the propeller. They also illustrate the presence of the rudder tip vortex, identified in earlier free stream rudder tests. The changes in forces and centre of pressure indicated the dominant effect of propeller thrust loading.

For the skeg rudder it was noted that whilst early stall occurred behind the skeg for the free-stream tests [16], it was delayed when operating downstream of the propeller, particularly as propeller thrust loading was increased, the strong periodic nature of the propeller induced velocities preventing the early development of stall aft of the skeg.

Molland *et al*. [18] describe a number of characteristics peculiar to the skeg rudder, which provide an improved understanding of how a skeg rudder behaves when operating behind a propeller and hull. The experiments had been carried out on a skeg rudder downstream of the propeller. It was found that the skeg rudder has a significantly lower lift curve slope compared with the all-movable rudder. As discussed in [16], the skeg rudder displays a discontinuity in its lift curve in the free stream due to the early stall of the movable part of the rudder aft of the skeg. Downstream of a propeller this phenomenon is seen to continue to exist at small thrust loadings, but decreases with increase in thrust loading and effectively disappears at the highest thrust loadings.

There is a significant increase in stall angle for the skeg rudder working aft of a propeller when compared with free-stream performance. There is evidence to suggest that these larger stall angles could be usefully exploited for ship installations in lower speed/high thrust loading manoeuvring situations; it would, however, mean fitting a steering gear that is capable of putting the rudder over to these large angles.

3.2.3 Influence of Hull Upstream

The basic influence of the hull is to slow down the flow into the propeller relative to the ship speed. Investigations were carried out [19], [20], to determine whether the hull upstream of the rudder-propeller combination would have a significant effect on the rudder characteristics. In particular, this would relate to the effect on the rudder force and moment characteristics and on the form or shape of the spanwise load distributions over the rudder due to the non-uniform ship wake. It was found that the hull had a very small effect on the rudder spanwise load distributions, total force and centre of pressure results. The overall results of the investigation indicated that the dominating effect of the propeller eliminates most of the likely effects of non-uniformities in the wake. This was an important result in that it also means that the extensive available data for rudder-propeller combinations in the absence of an upstream hull can be used at corrected input speed values with acceptable confidence. Further influences of a hull upstream of the propeller are described in section 3.2.5 when discussing flow straightening effects.

3.2.4 Low Speed and Four Quadrant Operation

Operation at low speeds and in different quadrants is an important aspect of ship manoeuvring. Detailed experiments were carried out on a rudder-propeller combination to investigate rudder performance at low speeds and in four quadrants of operation. These are very difficult areas of operation to model as in most cases the rudder is operating in a very confused flow. A range of experiments was carried out by Molland and Turnock [21] that explored the rudder-propeller interactions in these particular modes of operation. The majority of the tests were carried out in the 3.5m × 2.5m wind tunnel, applying the four quadrants of operation. Zero speed tests were carried out in a laboratory to simulate a true bollard pull (zero speed) condition.

Lift and drag data illustrate the changes in forces over the four quadrants. Spanwise pressure distributions identify the significant physical changes in the flow and hence rudder lift characteristics over the four quadrants.

At low and zero ship speed and at positive propeller revolutions the controlling influence of the propeller is clearly demonstrated and significant rudder forces can be generated.

The data were finally arranged as rudder lift (sideforce) coefficient at fixed incidence over the four quadrants, see Figure 5 in [23]. This treats the rudder plus propeller as a combination in isolation and is a very suitable presentation for manoeuvring simulations [23].

3.2.5 Flow Straightening Effects

When estimating the forces on a rudder, it is necessary to use the effective angle of attack to the flow. This may be different from the geometric angle of attack of the rudder. When rudder angle is applied a ship develops a yaw or drift angle which leads to a decrease in the effective inflow angle to the rudder. At the same time, the effects of a propeller and hull upstream of the rudder are to straighten the flow leading to a recovery, or increase, in the effective inflow angle to the rudder. It is important that these effects are incorporated and a net effective angle of attack used in any estimate of rudder forces.

Tests with the rudder operating downstream of a propeller and centreboards of different lengths and a representative hull are reported in Molland and Turnock, [19] and [20]. These Papers explain the experiments and results of the tests on the hull and centreline boards in the wind tunnel. The first Paper [19] provides an outline of the experiments and preliminary results and conclusions. The second Paper [20] reports on a re-analysis of the data and a presentation in a manner more suitable for practical design applications and validation purposes.

In [20], Molland and Turnock describe the investigations into the flow straightening effects on a ship rudder of an upstream propeller and centreboards and hull. A flow straightening factor is derived which depends on drift angle, propeller thrust loading and upstream hull form.

The overall results provide a better understanding of flow straightening effects and data for improving the prediction of manoeuvring rudder forces. The data for the centreline boards have applications for vessels with a relatively thin upstream skeg, whilst the data for the rudder plus propeller combination in isolation are suitable for vessels with open water sterns, such as twin screw vessels.

3.2.6 Some Applications of the Rudder-propeller Interaction Research

Some effects of rudder-propeller-hull arrangements on manoeuvring and propulsion are given in [22], where the effects of the position of the rudder relative to the propeller are described and discussed. A review of vessels in operation had indicated a wide variation in the choice of the relative positions of the rudder and propeller. Theoretical and experimental investigations were carried out which studied the influence of changes in the relative positions of the rudder and propeller in the longitudinal, lateral and vertical planes. The results of the experimental work are used to describe the implications for the design of aft end arrangements. It is concluded that significant changes in both propulsion and manoeuvring performance can occur when the relative positions of the rudder and propeller are altered. These lead to the need for careful consideration of these influences at the design stage in order to minimise propulsion losses and maximise manoeuvring performance.

Molland *et al.* [23] describe the incorporation of rudder-propeller interactions in manoeuvring and control algorithms and improvements in the simulation of ship manoeuvring, including four quadrant operation. In this Paper, a physically correct approach is postulated, termed an enhanced model, where the rudder plus propeller is modelled as a combination in isolation, as developed in the research programme, taking into account the governing parameters such as flow variables, rudder geometry, propeller variables and the relative positions and size of the rudder and propeller. The influences of an upstream hull and drift angle can then be applied in the form of velocity and flow straightening inputs to the basic isolated model of the rudder-propeller combination. This compares with traditional rudder models where the rudder characteristics in the free stream condition and the modifying effects on the rudder of the hull and propeller are treated as individual components of the complete system. Tests on the enhanced rudder model in a manoeuvring simulator indicated that, compared with the traditional model, the enhanced rudder model can lead to significant changes in the predicted side and axial forces and, consequently, in the better prediction of manoeuvring performance.

3.3 Numerical Techniques

Numerical techniques were developed which apply the propeller induced velocities as input to rudder theory, [24] and [25].

Rudder theory:

In the rudder theoretical analysis, lifting line theory is used. The theory is modified to suit the low aspect ratio rudder and to model the tip vortex by using superimposed twist corrections to the lifting line [24].

Propeller theory:

The propeller is represented by blade element-momentum propeller theory which had been developed for various propeller design uses, for example [26]. In this propeller-rudder interaction application it is used to estimate the propeller induced flow velocities and directions to be used as input to the rudder lifting line theory [24]. In this context, it has also proved useful in estimating the amount of twist required for twisted rudders.

Assisted by suitable empirical corrections derived from the experiments, the modified theory is able to represent well the rudder-propeller interactions. This has provided scope for parametric investigations into the effects of changes in rudder and propeller variables such as propeller thrust loading, rudder aspect ratio and propeller coverage of the rudder.

3.4 Rudder Research: Summary

Overall, the wind tunnel approach to deriving the characteristics of rudders and rudder-propeller interactions proved to be very successful. The experimental work, together with numerical modelling, has provided significant contributions to a fundamental understanding of rudder-propeller interactions and their effects on ship manoeuvring and control. Many of the experimental data are now used internationally as benchmark data for various rudder investigations and the detailed rudder performance characteristics incorporated in manoeuvring simulations.

4. Ship Design

4.1 Introduction

Ship design research carried out by the writer has entailed the development of new design synthesis techniques, in particular, relating to high speed semi-displacement monohulls and catamarans. The research considered two main themes:

(1) Design: derivation of design particulars, *including dimensions, masses, powering.*

(2) Concept exploration: concept exploration of alternative designs, *including dimensions, powering, seakeeping and techno-economics.*

In the 1990s there was a rapid growth in the use of high speed vessels, particularly ferries, including the growing application of the catamaran hull concept. At that time, information and data for these high speed vessels were sparse, including those for basic design and dimensions, powering, seakeeping and operational limitations. For these reasons, a research programme was initiated at the University of Southampton that examined the design, concept exploration and assessment of alternative high speed marine vehicle types. This would run alongside the existing programme of research into the resistance, propulsion and seakeeping properties of high speed mono and multihull vessels. It is important to note that for the fast ferry market, for the same task, the most suitable vessel for that task might be a monohull, catamaran or trimaran, namely different hull types. The research required the development of a comparative evaluation model of competing vessels or vessel types for a particular operation. This particular research centred on semi-displacement monohull and multihull craft and did not include SWATH, hydrofoil craft or hovercraft as possible options.

Over many years, investigations had been carried out by the writer into the modelling and synthesis of the analytical components of the ship design process, and developing computer based models of the technical design process for various ship types. Subsequently, with the growing interest in high speed ferries by the marine industry, the writer's work was directed at the design and concept exploration of high speed marine vehicles and the development of technical design and concept exploration algorithms, [27] to [34]. This provided a platform to apply many of the results of the various fast craft hydrodynamic investigations carried out by the writer. In particular, this included the task of effectively integrating the calm water resistance and propulsion estimates and seakeeping performance estimates into the overall approach, and developing preliminary design algorithms and decision making methods. This work was carried out by Postgraduates and Research Assistants under the supervision of the writer.

Molland and Karayannis [27] describe a model for the conceptual exploration and assessment of alternative high-speed marine vehicle types. This entailed the creation of a flexible modular framework for the derivation of the technical and commercial attributes for each vessel, together with the investigation and appraisal of alternative decision making techniques. A fundamental objective of the exploration model was to generate technical and commercial attributes and this approach is discussed. The creation of design modules is described including dimensions, powering (calm water resistance and propulsion), masses (hull, machinery, outfit and deadweight), seakeeping and stability. Qualitative costs are summarised including build costs and operating costs. Alternative decision making approaches are discussed, these usually entailing one of two basic approaches, namely operational simulations or multiple criteria techniques, or some hybrid derivative. An example application is described that compared alternative monohull and catamaran configurations to carry 500 passengers and 100 cars at 40 knots on the same route. It was found that whilst the calm water and added resistance characteristics for the two vessels were broadly similar, the seakeeping performance of the monohull was superior. This Paper provides an introduction to the exploration model, which is further developed and discussed in the later Papers [28], [29] and [30].

Molland *et al.* [28] describe the extension of the work reported in [27] to include build and running costs. In establishing and extending the database, useful discussions were held with design consultants, shipbuilders and operators. Decision making approaches are discussed and primary indicative attributes established, these being dimensions, build/repayment cost, fuel and seakeeping. Example case studies are used to illustrate the decision making process. The work demonstrated that the application of a limited number of attributes in the decision making process is attractive and feasible.

Karayannis *et al.* [29] describe the creation of a large design data base for high speed vessels for use at the preliminary design and exploration stages and an updated version of the design flow path, incorporating a displacement check. In particular, it describes the updated design algorithm/flow path for the derivation of dimensions for high speed mono and multihull vessels, Figures 2 and 3 in [29]. There are two flow paths in this approach to hull dimensions: namely one path based on hydrostatic and hydrodynamic requirements (for the principal parameters) and the other based on required passenger and vehicle areas.

The combination of both paths provides a solution for the dimensions. This provides an innovative and fundamentally new approach to deriving the dimensions of fast craft such as ferries where the design is area driven. Other data bases concerned masses, powering and seakeeping (based on [31] and [32]) together with initial cost estimates. Use of the data base is illustrated by case studies.

Molland *et al.* [30] describe design data and methodologies which provide a robust approach to the derivation of the dimensions of fast semi-displacement monohull and catamaran ferries at the preliminary design stage. The method of combining the requirements of adequate passenger and vehicle areas with suitable hydrodynamic parameters is described and reviewed, together with estimates of the ship mass and its important role in the derivation of the dimensions of such craft. A power estimate module is introduced. In this approach simple parametric regression equations are used which have been developed for use at the preliminary design stage to estimate the resistance of monhulls, together with the concept of wave resistance interference factors which have been developed for use with the monohull data to predict the resistance of catamarans. This allows power estimates to be made rapidly which are incorporated in the mass estimates used in the derivation of the dimensions. An improved method of predicting the seakeeping characteristics of fast ferries at the preliminary design stage is outlined, which is described in more detail in [32]. Example applications of the design methodologies are presented which demonstrate the sensitivity of ship size, dimensions and performance to changes in the specified input requirements.

4.2 Seakeeping Qualities of Monohulls and Catamarans

Research involvement in this area was stimulated by the work carried out on catamarans in calm water and the need to develop a better understanding of their performance in waves, both for design purposes and for determining operational limitations. EPSRC funding allowed an extensive parametric test programme to be carried out in head seas, Molland *et al.* [31]. The transfer functions obtained provide important input to voyage simulations at the design and concept exploration stage and reliable data for the validation of theoretical methods.

This research was extended with further EPSRC funding to cover the performance of multihulls in oblique seas, [31]. This entailed extensive experimental work with large (4m) radio controlled free running models in the Qinetiq Haslar Model Basin and the development of open sea testing techniques on Southampton Water. These head and oblique sea data were extended to produce spreading relationships for transfer functions relating the change of transfer function with heading angle. This broadened the applications of the head and oblique sea data at the concept design stage, Molland and Taunton [32]. In [32] the methods of assessing the seakeeping performance of competing high speed vessel designs are described and case studies are used to illustrate applications of the data and methodology.

4.3 Design and Operation Applications

Karayannis and Molland [33] describe a new and alternative approach to decision making in the fast ferry market, and focus on the key issues of customer satisfaction and sensitivity to changes in external factors, or design robustness. The decision making model focuses on the concept of design robustness by applying an algorithm based on a Taguchi-type approach. The structure of the model is such that the designs of various hull forms and types can be compared and ranked.

Finally, Karayannis and Molland [34] bring together and apply many of the design and operation attributes developed for the fast ferry research programme. A techno-economic simulation was carried out for both monohull and catamaran fast ferries on a particular cross channel route. The approach combined the technical design with the economics of operation to determine the sensitivity of the measure of merit (nominal ticket price) to changes in principal hull parameters, area per passenger (measure of quality of accommodation) fuel cost, service speed, passenger and car utilisation and speed allowed in restricted waters (such as for wash limits). The results provide a good insight into the influences of changes in design and operational features on overall operation. The approach has provided a useful tool for designers and operators to carry out systematic investigations at the concept and preliminary design stages.

4.4 Ship Design Research: Summary

The development of the design procedures demonstrated that that the design approach for fast semi-displacement monohulls and catamarans is significantly different to that for larger and slower displacement ships. The ship design research programme has led to innovative preliminary design algorithms for fast semi-displacement monohulls and catamarans. The derived data and developed design methodologies have made significant contributions to the design procedures and concept exploration for these vessel types.

5. Marine Current Turbines (MCTs)

5.1 Introduction

There was a growing interest in the 1990s in developing turbines for electrical energy extraction from marine currents. Energy extraction from marine currents offers the promise of regular and predictable energy, particularly where the mean peak tidal currents are over about four knots. The majority of the existing and proposed designs for energy conversion were designed around horizontal axis turbines. At that time, there was clearly a need to develop a deeper understanding of the operation and performance characteristics of marine current turbines (MCTs) in order to improve design and performance prediction procedures.

The writer was invited to help set up a new EPSRC funded research programme investigating marine turbines, based on technology transfer using his existing expertise in the design of marine propellers. The main objectives of the research programme were to determine the underlying physics of operation of horizontal axis marine current turbines and to derive a reliable set of turbine performance characteristics under controlled conditions. These results would provide essential information for the hydrodynamic design of MCTs and detailed data for the validation of numerical methods.

An extensive programme of model experiments was initiated to investigate the operation of MCTs. These entailed experiments with 800mm diameter turbines in a 2.4m × 1.2m cavitation tunnel and in a 60m test tank to gather performance characteristics, Bahaj *et al.* [35], together with 2D foil sections in a 0.5m × 0.5m cavitation tunnel to identify cavitation characteristics, Molland *et al.* [36]. The design and implementation of these sets of experimental investigations was carried out by a Research Assistant under the supervision of the writer.

Results of these experimental investigations have become the seminal work for those embarking on investigations into marine current turbines, particularly in the use of [35] and [36].

5.2 Discussion of MCT Experiments

5.2.1 Bahaj *et al.* [35]

The objectives of the work described in [35] were to establish a fundamental set of performance characteristics for a model of a typical MCT. This would entail deriving power and thrust coefficients for a range of rpm, flow speeds and blade pitch settings for various conditions. In order to simulate practical operating situations, these basic tests would be extended to include the secondary effects of yawed flow, changes in tip immersion, interference between twin rotors and likely areas of cavitation inception.

The basic performance characteristics using a 800mm model rotor, together with cavitation investigations, were obtained in straight flow in the 2.4m x 1.2m cavitation tunnel. The test rig included a dynamometer to allow measurements of turbine thrust and torque and a split turbine hub to allow easy changes of rotor blades and blade pitch angles. The tests resulted in a consistent set of data which showed an increase in power and thrust coefficients as hub pitch angle was reduced. The tunnel pressure was reduced, leading to low cavitation numbers when attached vortex cavitation was observed over 10% to 15% of the blades. Full scale cavitation numbers will be higher, indicating that with careful design of blade angles and tip speeds, it should be possible to prevent cavitation on full scale MCTs.

The yawed flow tests with the 800mm rotor(s), together with changes in tip immersion and interference between twin rotors, were carried out in the 60m test tank. There was little difference between the power and thrust coefficient results from the test tank and the cavitation tunnel, confirming the viability of using both facilities for such tests (although noting that cavitation cannot be simulated or observed in the test tank). The proximity of the free surface, with shallow tip immersion, had a significant effect on the power and thrust coefficients. The power coefficient was 10% to 15% lower than the deep immersion results and the thrust coefficient about 5% lower. These results demonstrate the need to have sufficient tip immersion to avoid a loss in performance. The yawed tests led to a decrease in power and thrust with increase in yaw angle, with power decreasing approximately with cosine of yaw angle squared and thrust as the cosine of yaw angle. These decreases can be allowed for when dealing with any changes in tidal current characteristics for a particular site. The results of the dual rotor tests showed relatively small changes even when the rotors were in close proximity. This should allow dual rotor systems to be employed without significant loss in performance.

5.2.2 Molland *et al.* [36].

The objectives of the work described in [36] were to examine performance characteristics and cavitation inception in some detail for different blade sections suitable for marine turbines. Section performance data, including cavitation characteristics are required for the detailed design of the turbine blades. It had initially been estimated and assumed that marine current turbine blades would suffer cavitation, especially near the tips of the blade and at top dead centre (at minimum immersion). Whilst there are plenty of cavitation data for marine propellers and foils, and lift and drag data for aerofoil sections, there was little available information on cavitation for the thick aerofoil type sections typically proposed for the blades of marine turbines. There was clearly a need for detailed information on the cavitation characteristics of these section types in order to incorporate a cavitation check in the design process. An investigation was therefore initiated into the lift, drag and cavitation characteristics of two-dimensional foil sections, which may typically be used as a starting point in the design of blade sections for marine current turbines.

Cavitation tunnel experiments were carried out in the 0.5m × 0.5m cavitation tunnel on four representative sections derived from the NACA series 4415, 6615, 63-215 and 63-815. Lift and drag over a range of incidence was recorded for each foil. One foil, 63-815, was tapped for pressure measurements. The experimental lift and drag data showed satisfactory correlation with published wind tunnel data. The onset of cavitation for various values of foil incidence and cavitation number was recorded. Cavitation inception curves (cavitation-free envelope or bucket) indicating the limits of back bubble, face and back sheet cavitation, were produced for each foil. These are suitable for direct use in the turbine blade design process. The sections were also modelled numerically using the two-dimensional panel code XFoil. The numerical pressure distributions showed good agreement with the experimental data and the numerical cavitation predictions in most cases showed satisfactory agreement with the experiments. It is considered that such numerical predictions could be used with reasonable confidence for predicting cavitation at the preliminary design stage.

Overall, the results of the investigation provide a better understanding of cavitation for these section types and essential performance data, necessary in the detailed design of marine current turbines.

5.3 Discussion of Numerical Predictions

The experimental work was subsequently extended to include the numerical prediction of MCT performance, Batten *et al*. [37]. In this Paper, the development of blade-element momentum theory (BEM) for the design of MCTs is described. Due to the narrow blades and near 2-D flow, the turbine can be modelled successfully using BEM. The theory is effectively the inverse of that successfully developed for marine propellers, such as that described in [25] and [26]. The theory was validated successfully using the cavitation tunnel test results for the 800mm model rotor reported in [35]. A number of cases were investigated to illustrate applications of the theory, based on the design of a three-bladed 20m diameter rotor. These entailed investigations of cavitation inception, the influence of the tidal velocity profile and the effects of an increase in blade drag due say to an increase in blade roughness and fouling. It was found that cavitation could occur with relatively shallow tip immersion. The effects of the tidal velocity profile led to fluctuations in blade loadings that should be taken into account in structural fatigue studies. It was found that blade fouling can lead to a significant decrease in power in certain cases.

Batten *et al.* [38] discuss the hydrodynamic design of marine current turbines, drawing on the results of the research programme. Blade element-momentum (BEM) theory [37] and cavitation data [36] are used to develop the design of a full scale turbine with a 16m diameter rotor. The BEM theory used in the numerical method is described in some detail and the theory is compared with experiments reported in [35]. The turbine design was matched to the tidal velocity and design speeds optimised. The results demonstrated that the numerical method is suitable for designing and optimising energy output with tidal data. The design of the support structure is considered, noting that as optimum energy output is approached there can be substantial increases in loads.

5.4 Marine Current Turbine Research: Summary

The research reported in this Section provided a significant early contribution to the fundamental design of horizontal axis marine current turbines. It was the first time research on MCTs had been carried out in a formal systematic way, providing an insight into the working of MCTs and creating reliable benchmark data. Consequently, [35], [36] and [37], in particular, are regularly cited by those embarking on investigations into Marine Current Turbines.

6. Summary and Conclusions

The Thesis has described contributions by the writer to original research. Significant contributions have been made in the fields of ship resistance components, marine rudders, ship design synthesis and marine current turbines.

Research into the resistance components of commercial catamarans arose from the need to improve the estimation of propulsive power for this developing ship type; this entailed establishing a fundamental understanding of its resistance components. The overall research programme included the testing of a series of catamaran models and the development of new theories for the prediction of wave resistance and wave wash. This work included the creation of an extensive resistance data base for high-speed semi displacement monohulls and catamarans. These still represent the widest available data set for round bilge commercial catamarans and are internationally accepted for benchmarking and design purposes. Evidence of the continuing use of this research on resistance components is illustrated by the citing of Reference [1] (over 240 citations) and [A1] (over 140 citations) by those embarking on investigations into the powering of catamarans. Further evidence of continuing use of the research is illustrated by the ongoing use of a book in which most of the experimental data, numerical work and practical outcomes of the research on ship resistance components and propellers have been published by the writer in the co-authored book, *Ship Resistance and Propulsion*. Reference [A15]. Over 1900 copies of the book (both editions) have been sold to date and over 440 citations made.

The rudder research entailed extensive experimental and theoretical studies into ship rudders and propellers and their interaction. The results of the work provide an insight into the physics of the flow, a detailed understanding of rudder-propeller interactions and their effects on rudder design and manoeuvring performance.

The rudder research has received international recognition and the experimental results have been adopted by many researchers and designers as benchmark data.

Evidence of continuing use of the research on rudders and propellers is illustrated by the ongoing use of a book in which most of the experimental data, numerical work and practical outcomes of the research on rudders and rudder-propeller interactions have been published by the writer in the co-authored book, *Marine Rudders and Control Surfaces* [A14]. Over 980 copies of the book have been sold to date and over 190 citations made.

The ship design research programme provided a platform to bring together and apply ongoing research by the writer including powering, seakeeping and techno-economics. The research led to the creation of new design algorithms for fast semi-displacement monohulls and catamarans; these provide an innovative and fundamentally new approach to the derivation of the dimensions of fast commercial craft such as ferries where the design is area driven. The design algorithms were extended to include the research into powering, seakeeping and techno-economics. This provides the ability to examine the influences of changes in design and operational features on overall operation, and to apply concept exploration, operational simulations and decision making methods when comparing alternative designs for a particular task.

The research into Marine Current Turbines provided a significant contribution to their early development, being the first time such research had been carried out in a formal systematic way. The research provided a fundamental understanding of the operation of MCTs, developed theories characterising their operation and created data which are still regularly used. Evidence of the continuing use of this research is illustrated by the citing of Reference [35] (over 800 citations) and [36] (over 130 citations) by those embarking on investigations into the design and operation of Marine Current Turbines.

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Papers included in the Thesis: Contributions by A.F. Molland and Others to each Paper

The following personal contributions by A.F. Molland to each Paper are shown as a percentage, made up of supervision of the research, estimate of share of the work and contributions to the writing of the Paper.

The ten most significant Papers are marked with an asterisk (*).

1. * Insel 30%, Molland 70%
2. * Molland 70%, Wellicome 10%, Couser 20%
3. Molland 70%, Lee 30%
4. Utama 30%, Molland 70%
5. * Molland 70%, Utama 30%
6. Couser 20%, Molland 60%, Armstrong 10%, Utama 10%
7. Couser 25%, Wellicome 10%, Molland 65%
8. Molland 70%, Barbeau 30 %
9. Moat 30%, Yelland 5%, Pascal 5%, Molland 60%
10. Moat 60%, Yelland 5%, Pascal 5%, Molland 30%
11. * Moat 25%, Yelland 5%, Pascal 5%, Molland 65%
12. Couser 20%, Wellicome 50%, Molland 30%
13. Molland 70%, Wilson 20%, Chandraprabha 10%
14. Molland 50%, Wilson 20%, Taunton 20%, Chandraprabha 5%, Ghani 5%
15. * Molland 50%, Wilson 20%, Taunton 20%, Chandraprabha 5%, Ghani 5%
16. Goodrich 30%, Molland 70%
17. * Molland 55%, Turnock 45%
18. * Molland 45%, Turnock 40%, Smithwick 15%
19. Molland 55%, Turnock 45%
20. Molland 55%, Turnock 45%
21. Molland 55%, Turnock 45%
22. Molland 55%, Turnock 45%
23. Molland 45%, Turnock 35%, Wilson 20%
24. Molland 100%
25. Molland 65%, Turnock 35%
26. Miles 20%, Wellicome 40%, Molland 40%
27. Molland 70%, Karayannis 30%
28. Molland 65%, Karayannis 25%, Couser 10%
29. Karayannis 30%, Molland 60%, Saraç-Williams 10%
30. * Molland 60%, Karayannis 15%, Taunton 15%, Saraç-Willams 10%
31. Molland 40%, Wellicome 30%, Temarel 5%, Cic 10%, Taunton 15%
32. Molland 60%, Taunton 40%
33. Karayannis 40%, Molland 60%
34. Karayannis 30%, Molland 70%
35. * Bahaj 5%, Molland 65%, Chaplin 5%, Batten 25%
36. * Molland 70%, Bahaj 5%, Chaplin 5%, Batten 20%
37. Batten 50%, Bahaj 5%, Molland 40%, Chaplin 5%
38. Batten 50%, Bahaj 5%, Molland 40%, Chaplin 5%
39. Molland 100%
40. Molland 50%, Turnock 50%

Appendix 1

1.1 Notation for the breakdown of catamaran resistance components

The notation developed in the research programme for the breakdown of the catamaran resistance components and the representation of viscous and wave interference effects, [1] and [2], has been adopted by many researchers and practitioners worldwide. Namely, from Section 2.2.3, the total resistance of a monohull can be described as:

$$C_T = (1 + k)C_F + C_W$$

and the total resistance of a catamaran can be described as:

$$C_T = (1 + \phi k)\sigma C_F + \tau C_W$$

where C_F is derived from the ITTC'57 correlation line, $(1 + k)$ is the form factor for a demihull in isolation, ϕ is introduced to take account of the pressure field change around the hull and would be calculated from an integration of the local pressures over the hull, σ takes account of the velocity augmentation between the two hulls and would be calculated from an integration of local frictional resistance over the wetted surface, C_W is the wave resistance coefficient for a demihull in isolation and τ is the wave resistance interference factor.

For practical purposes, ϕ and σ were combined into a viscous interference factor β, where $(1 + \phi k)\sigma C_F$ is replace by $(1 + \beta k)C_F$:

whence $$C_T = (1 + \beta k)C_F + \tau C_W$$

noting that for the demihull (monohull) in isolation, $\beta = 1$ and $\tau = 1$

Appendix 2

2.1 Ship Science Reports (Departmental Working Papers) ISSN 0140-3818

Where large quantities of experimental data had been generated, these were firstly reported in a University of Southampton, Ship Science Report. Developed theories were also firstly reported in a similar manner. These Reports are available free of charge from www.eprints.soton.ac.uk. Reports relevant to this thesis include:

A1. Molland, A.F., Wellicome, J.F. and Couser, P.R. Resistance experiments on a systematic series of high speed displacement catamaran forms: Variation of length-displacement ratio and beam-draught ratio. *University of Southampton*, *Ship Science Report No. 71,* SSSU71, ISSN 0140 3818, 1994, pp.82.

A2. Wellicome, J.F., Molland, A.F., Cic, J. and Taunton, D.J. Resistance experiments on a high speed displacement catamaran of Series 64 form. *University of Southampton, Ship Science Report No.106*, SSSU106, ISSN 0140 3818,1999, pp.19.

A3. Molland, A.F. and Turnock, S.R. Wind tunnel investigation of the influence of propeller loading on ship rudder performance. *University of Southampton*, *Ship Science Report No.46,* SSSU46, ISSN 0140 3818, 1991, pp.149.

A4. Molland, A.F. and Turnock, S.R. Wind tunnel tests on the influence of propeller loading on ship rudder performance: four quadrant operation, low and zero speed operation. *University of Southampton, Ship Science Report No. 64*, SSSU64, ISSN 0140 3818, 1993, pp.162.

A5. Molland, A.F., Wellicome, J.F. and Couser, P.R. Theoretical prediction of the wave resistance of slender hull forms in catamaran configurations. *University of Southampton, Ship Science Report No. 72,* SSSU72, ISSN 0140 3818, 1994, pp.24.

A6. Molland, A.F. and Turnock, S.R. Wind tunnel tests on the effect of a ship hull on rudder-propeller performance at different angles of drift. *University of Southampton, Ship Science Report No. 76,* SSSU76, ISSN 0140 3818, 1994, pp.188.

A7. Wellicome, J.F., Temarel, P., Molland, A.F. and Couser, P.R. Experimental Measurements of the Seakeeping Characteristics of Fast Displacement Catamarans in Long-Crested Head Seas. *University of Southampton, Ship Science Report No. 89,* SSSU89, ISSN 0140 3818, 1995, pp.65.

A8. Molland, A.F., Turnock, S.R. and Smithwick, J.E.T. Wind tunnel tests on the influence of propeller loading and the effect of a ship hull on skeg-rudder performance. *University of Southampton, Ship Science Report No. 90,* SSSU90, ISSN 0140 3818, 1995, pp.171.

A9. Wellicome, J.F., Temarel, P., Molland, A.F., Cic, J. and Taunton, D.J. Experimental measurements of the seakeeping characteristics of fast displacement catamarans in oblique waves. *University of Southampton, Ship Science Report No. 111,* SSSU111, ISSN 0140 3818, 1999, pp. 34.

A10. Molland, A.F., Wilson, P.A. and Taunton D.J. A systematic series of experimental wash wave measurements for high speed displacement monohull and catamaran forms in shallow water. *University of Southampton, Ship Science Report No.122*, SSSU122, ISSN 0140 3818, 2002, pp.194

A11. Molland, A.F., Wilson, P.A. and Taunton, D.J. Further wash wave measurements for high speed displacement catamaran forms in shallow water. *University of Southampton, Ship Science Report No.123,* SSSU123, ISSN 0140 3818, 2002, pp.156.

A12. Molland, A.F., Wilson, P.A. and Taunton, D.J. Experimental measurement of the wash characteristics of a fast displacement catamaran in deep water. *University of Southampton, Ship Science Report No.124*, SSSU124, ISSN 0140 3818, 2002, pp.62.

A13. Molland, A.F., Wilson, P.A. and Taunton, D.J. Theoretical prediction of the characteristics of ship generated near-field wash waves. *University of Southampton, Ship Science Report No. 125,* SSSU125, ISSN 0140 3818, 2002, pp. 33.

2.2 Books

Most of the experimental data, numerical work and practical outcomes of the research on ship resistance components, propellers and rudders are also published by the writer in co-authored books as follows:

A14. Molland, A.F. and Turnock, S.R. *Marine Rudders and Control Surfaces*, Butterworth-Heinemann, Oxford, UK, 2007. (Second Edition to be published in 2022).

A15. Molland, A.F., Turnock, S.R. and Hudson, D.A. *Ship Resistance and Propulsion*, Cambridge University Press, Cambridge, UK, First Edition 2011, Second Edition 2017. (First Edition also translated into Korean).

Appendix 3

Dynamometers – Purpose Designed and Built for the Experimental Investigations:

Accurate dynamometers are fundamental to obtaining reliable experimental data, measured by sensitivity, accuracy and repeatability. The following three dynamometers were custom designed and built for the various tests carried out by the writer and have played a significant role in gathering high quality data.

i) Five component wind tunnel dynamometer for rudders/control surfaces measuring: Lift, Drag, MomentX, MomentY, MomentZ, described in Molland [39]. The dynamometer was designed by Molland and built in house.

ii) Marine propeller: Wind tunnel dynamometer measuring: Propeller thrust, torque, revolutions, described in Molland and Turnock [40]. The dynamometer was designed by Molland and Turnock and built in house.

iii) Marine current turbine: Dynamometer for use in a cavitation tunnel and a test tank measuring: Turbine thrust, torque, revolutions, described in Bahaj *et al.* [35]. The dynamometer was designed by Molland and Batten, to the rigorous demands for working underwater, and built in house.

AFM
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