VERSUCHSANSTALT FÜR WASSERBAU UND SCHIFFBAU

Berlin Model Basin

THE METHOD OF QUASISTEADY PROPULSION AND ITS TRIAL ON BOARD THE METEOR

Report No. 1184/91

Contract No.	:	VWS 1474
Sponsor	:	BMFT: Bundesminister für Forschung und Technologie
Reference No.	:	524-3892 MTK 0431 0/A0
Reference Date	:	18. August 1987

This report contains
80 pages and
36 figures

Berlin, March 15, 1991

The Director — The Author

Prof.Dr.-Ing. H. Schwanecke — Prof.Dr.-Ing. M. Schmiechen

THE METHOD OF QUASISTEADY PROPULSION AND ITS TRIAL ON BOARD THE METEOR

Michael Schmiechen

ABSTRACT

In order to render the traditional method for the analysis of propulsion operational for full scale ships, it has been rationalized theoretically and practically. For that purpose an axiomatic model and a method for the identification of its five parameters under service conditions have been developed. Using a simple thrust deduction axiom it is possible to decouple the problems of resistance and wake and identify all parameters from only two steady states.

On model scale external forces producing load variations necessary for the parameter identification can be applied. At full scale ships under service conditions inertial 'forces' have to play the role of external forces and the fact has to be accounted for, that the system to be identified is part of a noisy feed-back loop. Accounts are given of the tests on board the METEOR, of the measurement technique, of the model tests, and of the results.

CONTENTS

SUMMARY 4

1. INTRODUCTION 8
   1.1 Problems 8
   1.2 Models 9
   1.3 Goals 11

2. MOMENTUM BALANCE 14
   2.1 Introduction 14
   2.2 Momentum, Forces 14
   2.3 Hull Towing Tests 16
   2.4 Thrust Deduction 18
   2.5 Parameter Identification 20
   2.6 Frequency of Revolution 22
   2.7 Conclusions 24

3. ENERGY BALANCE 25
   3.1 Introduction 25
   3.2 Energy, Powers 25
   3.3 Wake Fraction 26
   3.4 Open Water Tests 27
   3.5 Jet Power 28
   3.6 Lost Power 30
   3.7 Zero Thrust 32
   3.8 Thrust Deduction Theorem 34
   3.9 Conclusions 36

4. FULL SCALE TESTS 37
4.1 Introduction 37
4.2 Momentum Balance 37
4.3 State Variables 38
4.4 Waves, Wind 40
4.5 Parameters 41
4.6 Uncertainties 42
4.7 Speed over Ground 43
4.8 Trial Predictions 44
4.9 Conclusions 45

5. TEST TECHNIQUES 46
5.1 Introduction 46
5.2 Requirements 46
5.3 Solution 47
5.4 Calibration 48
5.5 Test Set-up 49
5.6 Test Procedure 49
5.7 Model Tests 51
5.8 Test Results 52
5.9 Conclusions 53

6. CONCLUSIONS 54
6.1 Review 54
6.2 Assessment 55
6.3 Prospects 57
6.4 Thanks 58

7. REFERENCES 59
7.1 Basic Work 59
7.2 Other Sources 61

8. SYMBOLS 65
8.1 Remarks 65
8.2 List 67

9. TABLES 72
9.1 METEOR and Model Data 72
9.2 METEOR and Propeller Data 73
9.3 Traditional Model Tests 74
9.4 Traditional Model Results 75
9.5 Rational METEOR Results 76
9.6 Rational Model Results 77
9.7 Rational Dummy Results 78

10. FIGURES 79
10.1 List 79

Figures 1-36

SUMMARY

The usual evaluation of the propulsive performance of ships has been proposed by R. E. Froude (1883) more than one hundred years ago. This traditional method is based on well understood pragmatic, but physically rather shaky conventions and can in practice only be applied on model scale. Consequently most of the knowledge on scale effects necessary for the prediction of full scale performance had to be derived from more or less vague theories.

In order to overcome the problems indicated the author has over the last decade systematically developed a rigorous systems identification technique in theory and practice. The final step in this thoroughly documented development was the full scale application on board the German research vessel METEOR under service conditions during a routine voyage into the Greenland Sea in November 1988.

The full scale tests as well as corresponding model tests at the Hamburg and Berlin model basins sponsored by the German Ministry for Research and Technology (BMFT) have now been finally analysed, so that results and conclusions can be presented. The present report is a rather straightforward translation of the final report on the project (Schmiechen, 1990).

The method for the identification of systems in noisy feedback loops described by the author earlier in a MIT report proved to be completely adequate. Even at severe sea states small quasisteady deviations from the steady average service conditions provide sufficient information for the identification of the five parameters, which have been coherently defined by the axiomatic model introduced ten years ago and further developed to a state of maturity now.

Using a hollow shaft fitted with strain gauges and calibrated at the Berlin Model Basin averages of thrust and torque have been measured 'continuously' over six or nine complete shaft revolutions. During the tests over a period of about half an hour the rate of revolution was linearly lowered by about 10 % and raised again without disturbing the ship operation itself and the other research activities on board.

Thus at any condition not only the mean values of thrust and torque but also their derivatives with respect to the rate of revolution and the ship speed over ground could be determined. The external forces causing the propeller load variation were the inertial 'forces' due to the very small de- and accelerations of the ship.

Due to the excellent technology, zero stability of less than 1 %, the results are perfect and totally consistent, in the mostly severe sea conditions at least in the statistical sense. The range of service conditions covered may best be described by the fourfold increase of resistance encountered

due to waves and wind as compared to more moderate weather conditions.

In heavy weather de- and accelerations chosen too cautiously to avoid hysteresis effects were too small for the purpose at hand. In future routine applications this can be changed without problems if necessary.

The corresponding model tests confirmed that most of the results are obscured by the well known scale effects at the propeller model. Consequently only propulsion tests at sufficiently high propeller Reynolds numbers have been evaluated and compared with the full scale conditions.

In order to explain and demonstrate the power and potential of the method the evaluation has been based on the results of only two steady states. To successfully use this very efficient model test technique with only two widely different external forces applied, the establishment of truly steady conditions in bearing friction and model speed are the only requirements.

Comparison of the full scale and model results show for example that the scale effect in the thrust deduction fraction is nearly exactly as predicted from earlier tests utilizing boundary layer suction to simulate full scale energy wake. The report provides a complete discussion of boundary layer effects in all efficiencies and factors of merit.

Additional tests with a model shortened according to Rader proved that the energy wake can in fact be influenced in the right direction. But the heavy forward trim at the necessary Froude numbers introduced additional effects in hull propeller interaction. So the extra costs for shorter models do appear not to be worthwhile for the type of testing proposed.

In conclusion the advantages of the proposed procedure may be summarized as follows:

Basis is a simple, explicit, coherent axiomatic model with the minimum possible number of five parameters, useful for the description of the propulsive performance in a wide service range.

The five parameters in question, i. e. the properties of the ship defined by the axiomatic model, may be identified from data of only two steady states of propulsion in the vicinity of the service condition.

For ships these two states can be derived by means of statistical methods from data obtained during quasi-steady deceleration and acceleration at service condition, even in heavy weather.

On model scale in principal only two steady states under two external forces have to be established. In practice a number of states will have to be realized in order to permit statistical evaluation and obtain confidence ranges for the results.

After the ship has been calibrated it can be used as a very sensitive measurement device itself, for the determination of the values of the effective resistance in waves and wind or ice, the speed of the water over ground, and others at any moment.

A 'drawback' of the method described is that it does not only require measurements of the propeller torque but its thrust as well. As has been demonstrated this is not a problem, neither in principle nor in practice. If one does without the measurements mentioned for one or the other reason, as e. g. Abkowitz does, one has to rely on extreme manoeuvres and loses the capability of the detailed, complete analysis.

In future the method may be applied for the evaluation of model tests and trials and for monitoring of ship performance in service, eventually increasing and improving the data base on scale effects. The next steps will be the integration into existing monitoring systems on board and the trial of remote monitoring.

The results so far imply that model testing in ice may be drastically rationalized by application of the procedure described, at the same time increasing the quality of the results. The application on full scale ice breakers will for the first time provide consistent values of the resistance under service conditions.

Due to the facts that the present axiomatic model is much closer related to physics than the traditional model and that it can be interpreted in terms of full scale data validation of CFD codes developed for integration into future ship design can of course only be successfully achieved along this route.

The possibilities of error analysis and quality control have been checked over and over again in the process of the evaluation. As a consequence of the extreme sensitivity of Froude's analysis it was found that at present systematic errors are still of primary concern. Before statistical methods could be applied sets had to be defined to which the methods apply.

As a new paradigm on hull-propeller interaction the method proposed may take some time to make its way into practice. But in view of modern optimum ship design including asymmetric afterbodies it is more than timely that the present, very unsatisfactory practice is supplemented and, maybe some day, replaced by the new, 'more rational' and 'more physical', still conventional procedure.

In view of the world-wide interest in the new procedure the 2nd International Workshop on the Rational Theory on Hull Propeller Interaction and Its Applications (2nd INTERACTION Berlin '91) will be held in Berlin on June 13 and 14, 1991 in cooperation with the Powering Performance Committee of the 20th ITTC.

1. INTRODUCTION

1.1 Problems

The traditional ship model test and evaluation technique is based on hull towing tests and propeller open water tests, i. e. on tests, in which the flows are very different from the flows at the corresponding propulsion tests and which can practically not be performed under service conditions with the corresponding full scale hulls and propellers.

Although these problems and their various consequences have been known for a long time there have been no coherent proposals for their solution except those developed by the present author over the last decade.

The problem of model resistance has been tackled by Keil at HSVA (1982) and by Tanaka at SRI (1985). The interpretation of the resistance concept by Tanaka is essentially equivalent to that of the author and has been proposed for the same reasons. For model tests Tanaka has also proposed quasisteady propulsion tests.

The problems of thrust and torque measurements have been investigated systematically by Mildner at VWS (1973). Using partially hollow shafts Bremer Vulkan could improve the sensitivity of the thrust measurement considerably (Nolte et al., 1989). But in principle systematic errors due to cross-talk can only be avoided by shafts calibrated before installation.

The problem of correlation between models and full scale ships has been treated by Holtrop (1978) using statistical methods and is in problem and goal essentially different from the present approach. The proposals by Abkowitz (1990) for the estimation of scale effects in the various propulsion factors are pointing in the right direction, but are based so far on traditional, thus incompatible model results.

A comprehensive description of all previous work by the present author concerning the various sub-problems has been published in 1985. The development of the methods of quasisteady propulsion has been finally documented in 1987.

In order to render the traditional method for the analysis and evaluation of ship propulsion operational for full scale ships, it had to be rationalized not only theoretically but experimentally as well.

For that end an axiomatic model and a method for the identification of its parameters had to be developed. After successful trial and application of the method on model scale the goal of the present project was to test it under service conditions on board a ship and to compare the results with those of corresponding model tests.

Due to the fact that full scale hull towing tests (Ferrando et al., 1990) and propeller open water tests are in general not possible, load varying tests have to be carried out to provide the information necessary for the analysis of hull-propeller interactions and the evaluation of the various efficiencies and factors of merit.

Only on model scale external forces, e. g. by means of weights or air screws, can be easily applied. The tests with jet propulsion on board the former "Meteor" (Schuster et al., 1967) will certainly remain a singular event.

The only way to realize load varying tests on board ships under service conditions is by quasisteady changes of the frequency of revolution. In this case the role of the external forces is played by the so-called inertial 'forces'.

For the measurement of thrust and torque on board a wide range of experiences was available at VWS with the design, calibration, and utilization of 5- and 6-component balances and with measurements on board.

In order to permit the evaluation of the load varying tests in the usual way axioms or conventions are necessary, which implicitly define resistance and propeller speed not directly measurable.

1.2 Models

On a very high level of consideration the evaluation of the propulsive performance of ships is the central part of a problem in the rational resolution of conflicts. The corresponding model (Fig. 1) shows the most important aspects. In this paper only the propulsive data and their evaluation in terms of the various propulsive efficiencies, i. e. the common, objective basis will be reconstructed in a rational fashion adequate for the problems at hand.

The individual, subjective assessment by the parties interested, e. g. shipbuilders, propeller manufacturers, marine engineers, ship operators, ship owners et al. will not be treated.

On the next lower level of consideration the problem of evaluating the propulsive performance of ships may be modeled as a problem in systems identification. As shown by the following exposition and results this format is adequate for the problems at hand. The same format is underlying the work of Abkowitz (1988, 1990), which is closely related to the work of the present author, but different in nearly every detail.

In order to shed additional light on the method proposed comparisons will be made with Abkowitz's procedure where ever possible. But no attempt will be made to develop and analyze that method explicitly and to suggest the possible improvements of that method if more complete measurements would be taken into account.

The model of the total ship system underlying the present work (Fig. 2), the 'identification' model, reflects the fact, that the hull-propeller system to be identified is part of a noisy feed-back loop. The model of the system to be identified, the axiomatic hull-propeller model, is the mathematical description of the following three models.

The theory of hull-propeller interaction is based on the concept of the equivalent propeller in the energy wake alone, i. e. 'far behind the hull'. The theory of the resistance is based on the concept of the equivalent state of vanishing thrust. And, last but not least, the theory of the propeller speed is based on the concept of the equivalent open water propeller.

'Equivalent' is a shorthand notation for 'corresponding to the observed behaviour during load varying tests in the vicinity of the service condition of interest'. The load variations, i. e. small deviations from the service condition, are necessary for the identification of the parameters.

It will have become evident at this point that each level of consideration requires its own adequate model. As a matter of fact the models of the higher levels are usually not stated explicitly, so that the most important features remain unspecified with all the consequences.

Usually the axiomatic models are referred to as mathematical models. The fact, that the models are mathematical, is certainly very important for their practical applications, but is their least important aspect.

Much more important is the fact, that in terms of ethics they are conventions, i. e. principles for the rational resolution of conflicts, which have to be agreed upon by the parties interested and willing to join that process.

In logical terms the models are axiomatic systems, which cannot be proved, but only prove to be useful in practical applications, i. e. in terms of the science process they are working hypotheses. In terms of semiotics models are languages, of which consistency must be required in the first place. And this can only be guaranteed if the models are explicit.

The axiomatic hull-propeller model corresponds in all details exactly to the hydrodynamic theory of the ideal propeller in uniform energy and displacement wakes. In this limiting case it becomes identical with that theory as necessary. Surprisingly enough that theory is hardly known, although it provides important insights into the hull-propeller interactions.

For real propellers in non-uniform wake the 'ideal' theory may be considered as an approximation of the actual situation. Much more interesting is the approach, proposed in 1980 by the present author, to use it as an axiomatic system for the implicit or coherent definition of quantities, which cannot be defined otherwise, namely the resistance and the propeller speed.

As with all axiomatic theories only plausibility and effectiveness are decisive for their acceptance and applications. Proofs can only be provided for their consistency, but not for their truth. Although these facts are pretty evident and widely known, their implications and consequences are hardly accepted.

Due to Abkowitz's well understood pragmatic limitation to the measurements of the speed and the frequency of revolution and the subsequently necessary additional axioms, i. e. the different axiomatic hull-propeller model, and extreme manoeuvres to be physically executed, i. e. the other information, and last but not least due to the different algorithm for the identification of the parameters the results of the two methods are not directly comparable.

1.3 Goals

The overall goal of the project was the first trial on board of a method developed for the analysis of the interactions between hulls and propellers of full scale ships, after it had been successfully tested in model tests. The results were to be compared with those of corresponding model tests, thus providing, at least for the case investigated, data permitting a complete analysis of scale effects.

The procedure was so mature after years of basic work of the present author that the trial did not include any risks. The problems were to perform the measurements of hull speed and of propeller thrust and torque with the accuracy necessary and to adequately deal with the stochastic disturbances using statistical methods, as had been done at the model tests.

The long range goal of the project was to provide a method, which permits with minimum disturbance, if any, of the ship operation a quasi-continuous monitoring of the propulsion, e. g. for optimal control. The comparison with model test results will permit a sound research into the scale effects necessary for reliable power predictions, but hitherto impossible due to the lack of adequate full scale measurements, corresponding model tests, and their analysis.

The method tried in model tests is based on measurements of ship speed, propeller thrust and torque taken at load varying conditions in the vicinity of the service condition under investigation caused by quasisteady, else arbitrary variations of the frequency of revolution of the propeller.

The extensively documented development of the rational theory of hull-propeller interactions (see 7.1) started with the solution of the evaluation problem, i. e. the construction of the abstract axiomatic theory. The main focus of this work are the measurement of the propulsion data and their connection with the concepts of the abstract theory, i. e. the construction of the interpretation theory, the second part of any rational theory.

As already mentioned the abstract theory essentially consists of the models of the equivalent propeller in the energy wake alone, i. e. 'far behind the ship', of the equivalent propeller at vanishing thrust and of the equivalent open water propeller. All three equivalent propellers are in general not physically realizable, but purely mathematical constructs on the basis of the data observed in the behind condition.

The whole theory will be developed here in two stages as pragmatic as possible. In view of the difficulties encountered a more rigorous procedure has been adhered to so far. But this deductive procedure, adequate for the problems at hand, proved to find little acceptance despite its great transparency and efficiency.

As acceptance by the experts concerned is one of the essential prerequisites for the introduction of new conventions, the goal of this exposition is the stepwise, easily to be followed reconstruction of the theory and its applications. For this purpose the exposition runs reverse to the project and utilizes know-how obtained during the project, especially during the analysis of the data from METEOR and its model.

The exposition will closely resemble the basic knowledge of naval architects and tell in a continuous story the problems and the solutions suggested. This journalistic or belletristic style still requires the reader to identify himself with the story, i. e. to realize that the problems are his problems and to jugde the solutions proposed and accept them or, if possible and/or necessary, replace them by more adequate ones.

For didactic reasons the theory will first be developed for models in calm water, where external forces producing load variations can be easily applied. In a first step the considerations will be limited to the momentum balance and the problem of thrust deduction, while in the second step the energy balance and the wake problem will be treated.

Only after that full scale ships will be considered, where under service conditions inertial 'forces' have to play the role of external forces and the fact has to be accounted for, that the system to be identified is part of a noisy feed-back loop.

The description of the tests on board the METEOR, of the measurement technique, of the model tests, and of the results will be very short after that. The paper will conclude with an evaluation of the project and an attempt to outline further developments possible and necessary.

2. Momentum balance

2.1 Introduction

Although the propulsion of ships is an ordinary problem in mechanics, the basic equations of mechanics are rarely explicitly stated. Instead most of the fundamental relations are treated implicitly, i. e. they are assumed to be known and understood in the same way by the parties interested. The necessary consequences of this traditional 'agreement' on non-explicit models are surprisingly vague ideas, to say the least, on very simple fundamental facts.

These deficiencies can be avoided, if all fundamental relations are explicitly reconstructed starting from the fundamental equations, in this chapter from the momentum balance. The goal is to structure the presentation in such a way, that after the introduction of a new concept all implications are being developed.

After momentum and forces resistance and thrust deduction will be investigated and a thrust deduction axiom will be introduced, which coherently defines resistance and thrust deduction and permits their identification. The chapter will close with applications of the results obtained up to that point.

2.2 Momentum, Forces

Starting point of the whole consideration is the equation of longitudinal motion or momentum, i. e. the balance of longitudinal momentum or quantity of motion, in the usual format

$$d(M\ V)/dt = M\ A = T_E + F - R$$

for quasisteady changes, where no past history or memory effects have to be taken into account.

The symbols denote:

$M = m + m_X$	the total inertia of the ship,
$m = const$	the mass of the ship itself,
$m_X = const$	the hydrodynamic inertia of the ship,
V	the speed of the ship,
t	the time,
$A = dV/dt$	the acceleration of the ship,

T_E	the effective thrust of the propeller,
F	the total external force,
R	the total resistance.

The grouping of forces acting on the ship into total external force and resistance is not unique. In view of the interactions between hull and propeller the resistance in the narrow sense should include only forces having influence on the interactions. In this sense wave, wind, and ice forces may at least in a first approximation be treated as components of the external force.

The effective thrust of the propeller, the supply available to overcome the demand, is in general less than the thrust T measured at the propeller shaft, due to the displacement wake and the correspondingly increased pressure level on which the propeller operates.

The equation

$$T_E \text{ Þ } T\ (1 - t)$$

defines the thrust deduction fraction t, which has evidently 'nothing' to do with the resistance.

Denoting two different quantities by the same symbol t is of course very unsatisfactory. It may be accepted here, as it will not lead to confusion, the thrust deduction fraction being a global quantity in the context of this paper, while the time is rather a local quantity.

The rate of change of the momentum, the storage term of the balance, usually called inertial 'force', may be treated as part of the external force and is usually not stated explicitly. This is very dangerous as subsequently it may be forgotten. In view of the very large ship or model masses it may constitute a substantial contribution to the momentum balance, even at extremely small accelerations of less than a thousandth of the gravitational acceleration.

Exactly this fact can be and has been used to identify thrust deduction and resistance at full scale ships as will be explained later. In other cases the fact stated cannot be ignored without penalty. During the evaluation of the METEOR model tests it could be shown, that careless averaging of the data completely fouled the results. This problem has already been discussed by Jinnaka (1969).

Now two steady states are considered at the same speed

$$V_1 = V_2 = V\ ,$$

at which mass and resistance of the ship are the same as well:

$$M_1 = M_2 = M \ ,$$

$$R_1 = R_2 = R \ ,$$

and the corresponding accelerations, thrusts, and external forces are

$$A_1, \ A_2, \ T_1, \ T_2 \text{ and } F_1, \ F_2 \ .$$

In view of the following it is appropriate to introduce already at this point the corresponding shaft frequencies of revolution and torques

$$N_1, \ N_2 \text{ and } Q_{P1}, \ Q_{P2} \ .$$

Depending on the situation a number of fundamental problems have to be distinguished now, only three of which will be considered in the following.

2.3 Hull Towing Tests

Traditionally steady states

$$A_1 = A_2 = 0$$

are 'assumed', in practice they have to be provided for, and the resistance is assumed given, namely to be equal to the towing resistance of the hull determined in a towing test:

$$R = R_T \ .$$

The problem is that in many cases this traditional axiom cannot be applied in a meaningful way, e. g. in cases where towing tests cannot be performed, as e. g. at full scale, or lead to results different from those under service conditions, as e. g. at model scale for unconventional afterbodies, high speed crafts, and ice breakers.

According to the traditional view the momentum balance results in the relation

$$t_i = (T_i + F_i - R) / T_i = $$

$$= 1 - (R - F_i) / T_i$$

for the unknown thrust deduction fraction. As the values of thrust and resistance are of the same order of magnitude the determination of the thrust deduction fraction along this route is not only affected by the systematic errors mentioned but additional random errors, even under the rather ideal conditions in towing tanks.

Two typical widely different examples are high speed crafts and ice breakers. For both types the resistances in towing tests and in propulsion tests are different, in the first case due to differences in trim, in the second due to differences in ice properties.

While for high speed crafts the problem has led to a solution proposed by Tanaka (1985) much along the line of thought advocated here, the 'ice breakers' are just becoming aware of the problem (19th ITTC, Madrid 1990), still being trapped in the traditional misconception outlined.

Under the acceptable assumption that systematic errors in model basins do not change over the years, the practice of yards and owners to file statistics by model basins (Langenberg's discussion of Harvald and Hee, 1988) is very reasonable, but certainly not comforting and acceptable for the community in the long run.

The situation is unsatisfactory in view of the principle of objectivity, implying the properties of a ship to have objective values, at least relative to a mathematical model and a method for the identification of its parameters. Already small differences in the model and the method of identification result in remarkable differences. The reason for this sensitivity is the essentially differentiating nature of Froude's method of analysis, which is 'only' rationalized here.

Although the primary goal of the ITTC is to resolve problems of this nature, the problem outlined is not yet being acknowledged as such and adequately discussed. And the new Working Group on Error Analysis and Quality Assurance (ITTC, 1987/90) cannot resolve the subsequent problems as long as the Powering Performance Committee has not provided a generally accepted standardized procedure.

Due to the fact that the towing resistances of full scale ships are unknown, the corresponding thrust deduction fractions are axiomatically assumed to be equal to those of their models under the action of well defined external forces compensating for the only partial dynamic similarity of prototype and model.

Already simple theoretical considerations of ideal propellers in uniform wakes show however, that this second traditional axiom is unsatisfactory as well. The reason is that the ratio of displacement and energy wakes, apart of the propeller loading the second parameter to determine the thrust deduction fraction, is different at model and full scale, at least in the traditional model test technique using an external force to compensate for the relatively too large model resistance (Schmiechen, 1985).

2.4 Thrust Deduction

The rational procedure differs from the traditional in that the resistance of the hull under service condition, even on model scale, is considered as a 'purely theoretical' quantity, which cannot be measured directly.

For the exposition of the principles steady states are assumed given as before, i. e. carefully provided for. With the 1500 kg METEOR model in the towing tank no completely stationary states have been obtained, even without control of the frequency of revolution. Consequently steady states on which evaluations are based have been identified by carefully filtering the data. As mentioned before straightforward averaging has been shown to be completely inadequate for the purpose at hand.

Another procedure which has been followed in earlier quasisteady tests is the complete statistical evaluation including the inertial terms based on the accelerations determined from measurements of the longitudinal model displacements relative to the carriage (Schmiechen, 1987/8).

During careful tests of the method at the Hamburg Ship Model Basin a hysteresis has been observed at the frequencies necessary on model scale (Laudan and Oltmann, 1988). But it could not be finally resolved whether this was due to hydrodynamic causes or to the use of different filters for different signals.

If the resistance is not known the momentum balances for the two steady states are not sufficient to determine thrust deduction fractions for the two states and the resistance. This situation cannot be changed by adding additional steady states, as with any state another unknown thrust deduction fraction is added.

This problem of missing 'closure' can simply be solved by postulation of an additional condition, i. e. an axiom on the thrust deduction. The most pragmatic approach is to introduce the quadratic function

$$t = t_{H0} + t_{H1} J_H + t_{H2} J_H^2 / 2$$

of the apparent or hull advance ratio

$$J_H \text{ Þ } V / (D N) ,$$

with D denoting the diameter and N the frequency of revolution of the propeller.

The three unknown thrust deduction parameters t_{Hi} and the resistance can now at least in principle be determined from the momentum balances of four steady states. In view of the omnipresent noise in practice measurements will have to be taken at many more different states, and optimum estimates of the unknowns together with confidence intervals will have to be determined.

The technical details of this procedure do not pose any problems, but they will not be described here, as the confidence intervals will be unacceptable in case of rather small excursions from the service condition as in the ship case to be discussed later.

This fact would not create any difficulties, if the results would only be used for purposes of interpolation. But if the parameters are considered as physical quantities themselves and used for extrapolation, maybe only hypothetical, the only solution of the problem is to reduce the quadratic law at least to a linear one or even further.

After careful consideration of the various possibilities all the following work was based on the simple axiom

$$t = t_H \, J_H \, .$$

This model has the advantage of greatest simplicity and numerical stability, getting along with only one parameter and consequently only two steady states for the identification of the remaining parameter and the resistance. And from quasisteady tests on board ships more states cannot be constructed anyway.

At hypothetically infinite propeller frequency of revolution, i. e. at infinite propeller loading, the model provides for vanishing thrust deduction fraction:

$$t = 0 \quad \text{at} \quad J_H = 0 \, .$$

This state is of course different from the state of vanishing velocity, physically to be realized in Abkowitz's procedure.

More important is the principal question whether the axiomatic definition of the resistance implied by the simple model is meaningful. The answer to this question is of course not the 'accidental' coincidence of the traditional and the rational resistances of the METEOR model.

At the model speed

$$V = 1.688 \text{ m/s}$$

the towing resistance

$$R_T = 53.38 \text{ N}$$

was measured at HSVA, while from propulsion tests at VWS the resistance

$$R = 54.48 \text{ N}$$

was obtained using the simple thrust deduction axiom.

The simple axiom was in the first place introduced to check another one, which had been used successfully before

(Schmiechen, 1987/88), but resulted in a very involved identification procedure and for that reason alone had little chance of general acceptance.

During the evaluation it became evident, that the simple axiom proposed now and decoupling the thrust deduction and wake problems is at least approximately equivalent to the former

$$w_E = \text{omeg } w \ ,$$

postulating proportionality of energy and total wake fractions.

2.5 Parameter Identification

In the deterministic case the thrust deduction parameter is determined after elimination of the unknown resistance, i. e. from the difference of the momentum balances for the two steady states:

$$t_H = D/V\ (T_2 + F_2 - T_1 - F_1) \;/\; (T_2/N_2 - T_1/N_1)$$

and the resistance at the given speed may be obtained from one of the two equations

$$R = T_i\ (1 - t_H\ V\ /\ (D\ N_i)) + F_i\ .$$

It is worth noting here that the two unknowns are of very different nature. While the thrust deduction parameter is a property of the system, invariant in a wide range of service conditions, the resistance must be considered as rather 'accidental'.

In case of more than two states or multiple measurements the system of linear equations

$$R + T_i/N_i\ V/D\ t_H = T_i + F_i\ ,$$

or

$$a_{ij}\ x_j = b_i\ ,$$

with

a_{i1} Þ 1 ,

a_{i2} Þ $T_i/N_i\ V/D$,

x_1 Þ R ,

x_2 Þ t_H ,

b_i Þ $T_i + F_i$,

to be solved by a least square fit is simply the system of momentum balances for the states observed. Optimum estimates of the unknowns are obtained as solutions of Gauss' normal equation

$$a_{ik}\ a_{ij}\ x_j = a_{ik}\ b_i\ .$$

In this shorthand notation equal indices imply summation according to Einstein's convention.

If the model, i. e. the hull-propeller system, has been 'calibrated' in this way, the effective or net thrust

$$T_E \text{ Þ } T\ (1 - t_H\ V\ /\ (D\ N))$$

may be determined as soon as the speed of the model, the frequency of revolution, and the thrust of the propeller have been measured.

With the resistance and the effective thrust the external force is given:

$$F = R - T_E\ .$$

Possible applications of this procedure are measurements of the effective resistance in waves, wind, and ice.

In view of the fact that a unique separation of resistance and external force is not possible, it is often convenient to introduce the effective resistance

$$R_E \text{ Þ } R - F$$

and measure it in terms of the effective thrust

$$R_E = T_E\ .$$

At steady motion both quantities, supply and demand, although not identical, but different in nature, are equal, i. e. the supply meets the demand.

2.6 Frequency of Revolution

On the other hand an effective resistance may be given at some speed, e. g. by crude estimation or some more elaborate prediction method, and the operating condition of the propeller may be in question.

In order to solve this problem the propeller thrust has to be known as function of propeller frequency of revolution and hull speed. In the present investigation the data could be described by the model

$$T = T_0\ N^2 + T_H\ N\ V$$

and the thrust parameters T_0 and T_H have been determined from the same data as the thrust deduction parameter and the resistance.

Only after the identification of the parameters the model has been transformed into the normalized format

$$K_T = K_{T0} + K_{TH} J_H$$

with

$$K_T \text{ Þ } T / (rho\ D^4 N^2) ,$$

$$K_{T0} \text{ Þ } T_0 / (rho\ D^4) ,$$

$$K_{TH} \text{ Þ } T_H / (rho\ D^3) .$$

It is important to deal explicitly with the problem of 'weighing', which one cannot escape, as any format chosen for fitting the data by the model implies some sort of weighing the data. Consequently the results depend in all cases of interest, i. e. in the presence of noise, on the format chosen. This fact alone requires rigorous standardization, if results are to be comparable.

After various considerations and numerical tests the physical quantities have been faired in this study, as they are of primary interest. It is felt that more fundamental investigations are necessary before the procedure can be safely standardized. Evidently this is a problem of systematic errors or bias in parameter identification.

Further introducing as standardized quantities the coefficients of the effective thrust and resistance

$$C_E \text{ Þ } T_E / (rho\ D^2 V^2) ,$$

$$C_R \text{ Þ } R_E / (rho\ D^2 V^2) ,$$

the equation to be solved is

$$C_E = C_R$$

or with the data given

$$(K_{T0} + K_{TH} J_H) (1 - t_H J_H) = C_R J_H^2 .$$

This is a quadratic equation for the hull advance ratio. With its solution and the given hull speed one obtains the frequency of revolution

$$N = V / (D J_H)$$

and subsequently the thrust

$$T = rho\ D^4 N^2 (K_{T0} + K_{TH} J_H) .$$

After the introduction of the model equation for the thrust and the 'calibration' only two state variables need to be measured to derive the other quantities. If e. g. hull speed and propeller frequency of revolution are measured, the hull advance ratio and other quantities considered so far can be determined. If the thrust is measured instead of the hull velocity the latter may be determined, see 4.7.

It has been tacitly assumed up to now that the parameters of the thrust function of the propeller are independent of the frequency of revolution of the propeller, i. e. of the Reynolds number of the flow around the propeller profiles. But this assumption is adequate only if the frequency of revolution exceeds a certain critical value.

While this condition always holds for full scale propellers it does in general not hold for model propellers as tests are usually carried out according to Froude's condition of similarity in order to scale the wave pattern properly.

The results of tests carried out at HSVA (Table 9.4, Figure 30) show at low speeds, i. e. low frequencies of revolution, very considerable deviations from the simple Newtonian behaviour, which are of course not due to Froude, i. e. wave effects, but to Reynolds, i. e. viscosity, so-called scale effects at the propeller.

These effects are well known from propellers in the open water condition (e. g. Meyne, 1972), but are systematically taken into account in propulsion analysis only in exceptional cases, if absolutely necessary (Grothues-Spork, 1965).

Usually open water tests are carried out at frequencies of revolution well above the critical and the results are used for the evaluation of propulsion tests despite the fact that those are performed at much lower frequencies of revolution.

The usual 'argument', i. e. rather excuse, is that the model propeller in the behind condition is working in a turbulent wake and will 'consequently', i. e. hopefully, exhibit no scale effects. The results drastically show that this is not the case, at least not for the model investigated and at frequencies of revolution less than the critical value in the behind condition, lower than the one in the open condition mentioned before.

The resulting problems for the traditional method and possible solutions shall not be discussed here, as the whole method is in doubt. In view of the goal of this study a pragmatic approach has been taken and only the tests at the highest Froude number investigated at VWS, providing for frequencies of revolution above the critical in the behind condition, have been analysed by way of example (Tables 9.6 and 9.7).

The purpose is to reduce scale effects as far as possible to those of the hull alone and permit evaluation of the model data according to exactly the same model as full scale data. The latter condition has very high priority in view of the aforementioned sensitivity of the whole procedure, while effects of the Froude number on hull-propeller interaction appear to play a minor role as the comparison of model and dummy results shows.

2.7 Conclusions

The systematic reconstruction and detailed discussion of the momentum balance has provided insights, in principle not new, but obscured by the traditional presentation and test methodology misusing propulsion tests to solve quadratic equations.

Contrary to the procedure of Abkowitz partial models and complete measurements discussed here permit the separate identification of all quantities considered so far. This technique has the advantage of great transparency and numerical stability.

The separate solution of the resistance problem achieved by the very simple thrust deduction axiom closely resembles the traditional procedure without requiring towing tests or large departures from the propulsion condition under investigation.

3. Energy balance

3.1 Introduction

After the discussion of the momentum balance with all its aspects the energy balance will now be studied. Following the introduction of the concepts of the propeller speed of advance and wake the traditional and the rational procedures for analysis of the propeller action are explained.

The rational procedure is characterized by the introduction of the fundamental concept of the jet power of the propeller and the model of the equivalent open water propeller, which will be developed in detail. Finally the thrust deduction theorem will be derived from the model of the equivalent propeller in the energy wake alone, i. e. 'far behind the hull'.

3.2 Energy, Powers

Multiplication of the momentum balance by the hull speed leads to

$$M\ A\ V = T\ (1 - t)\ V + F\ V - R\ V$$

or

$$dE_k/dt = P_E + P_F - P_R\ ,$$

i. e. the balance for the kinetic energy

$$E_k \text{ Þ } M\ V^2 / 2$$

with the effective propeller power

$$P_E \text{ Þ } T_E\ V\ ,$$

the power of the external forces, e. g. the towing power

$$P_F \text{ Þ } F\ V\ ,$$

and the resistance power

$$P_R \text{ Þ } R\ V\ .$$

Traditionally no distinction is being made between the resistance power and the power of the external forces, e. g. the towing force. The reason is of course that traditionally the resistance is axiomatically equal to the towing resistance of the hull without propeller.

Due to the fact that these quantities may be equal, but are not identical, being different in nature, it is suggested that they are distinguished by name and symbol as proposed in order to avoid further confusion.

The same holds for the traditional confusion of the effective propeller power and the resistance power resulting from the equilibrium at steady state propulsion without external forces acting.

In the present context the condition

$$P_R = P_F$$

is satisfied only at steady states with vanishing effective thrust. In general the flow around the hull at this state is different from the flow at the towing condition without propeller.

As the flow at vanishing thrust and at service condition may be very different, e. g. due to changes in separation, only the equivalent state of vanishing thrust, i. e. a theoretical construct derived from data at service condition, is taken into account in the rational procedure.

It is once again noted here that the storage or inertial term is in general not negligible even at very small accelerations due to the very large model and ship masses.

3.3 Wake Fraction

So far the consideration of the energy balance could produce only little new insight as it is only the momentum balance in another guise. New aspects result from the introduction of new concepts in connection with the effective propeller power.

The central concept here is that of the propeller speed of advance relative to the water, which differs from the hull speed by the wake, i. e. energy and displacement influences of the hull on the flow around it.

With the relative wake or wake fraction

$$w \;\text{Þ}\; (V - V_P) / V \;\text{Þ}\; 1 - V_P / V$$

the effective propeller power is

$$P_E \;\text{Þ}\; T\,(1 - t)\, V_P / (1 - w) \;.$$

With the thrust power of the propeller

$$P_T \;\text{Þ}\; T\, V_P$$

and the hull efficiency

$$eta_{ET} \;\text{Þ}\; P_E / P_T \;\text{Þ}\; (1 - t) / (1 - w)$$

another expression is

$$P_E \;\text{Þ}\; eta_{ET}\, P_T \;.$$

If in addition the shaft or propeller power

$$P_P = 2\ \mathrm{pi}\ N\ Q_P\ ,$$

the efficiency of the propeller

eta_{TP} Þ P_T / P_P ,

and total propulsive efficiency

eta_{EP} Þ P_E / P_P

are introduced, the relation

eta_{EP} Þ $\mathrm{eta}_{ET}\ \mathrm{eta}_{TP}$

is obtained, i. e. the usual break down into hull and propeller efficiencies.

It is noted here explicitly that up to now all this has evidently nothing to do with physics, but only nominal definitions have been introduced so far.

3.4 Open Water Tests

Traditionally the advance speed of the propeller V_P is axiomatically postulated to equal the advance speed of the propeller V_A in open water:

$$V_P = V_A\ .$$

As the traditional resistance axiom this axiom is in many cases not applicable or not meaningful, e. g. if open water tests cannot be performed in principle or in practice or if open water tests lead to results very different from those under service conditions.

This is the case for propellers of full scale ships in general and for model propellers in 'very' non-uniform wakes, for wake adapted propellers, and for propellers in ducts and tunnels.

The propeller speed is traditionally identified either from the thrust or the torque identity

$$V_{PT} = f_{TP}{}^{I}(K_T)\ D\ N\ ,$$

$$V_{PQ} = f_{QP}{}^{I}(K_{QP})\ D\ N\ ,$$

with the advance ratio of the propeller

J_P Þ $V_P / (D\ N)$,

the normalized thrust and torque functions

$$K_T = f_{TP}(J_P) ,$$

$$K_{QP} = f_{QP}(J_P)$$

of the propeller in open water and the corresponding inverse functions f_{TP}^I and f_{QP}^I, respectively.

One problem with this procedure is that as a consequence of the non-uniformity of the wake the values of the two propeller speeds introduced are different. For the solution of this problem various proposals have been made without much success. The pragmatic introduction of the rotative efficiency is the accepted practice.

It is really surprising that for more than one hundred years now a procedure for the evaluation of the propulsive performance of ships has been used, that cannot be applied full scale and is very unsatisfactory on model scale.

The problem on model scale is in general complicated by effects of viscosity. The goal of this work is not to discuss these problems further and try to solve them in the traditional context, but totally replace the traditional by a rational procedure.

3.5 Jet Power

In the rational procedure the propeller speed is considered, as the resistance before, as 'purely theoretical' quantity, which cannot be measured directly, not even on model scale. For its coherent axiomatic definition the concept of the jet power of the propeller is fundamental.

Later further concepts will be introduced, which are not used traditionally, although they are absolutely necessary for the adequate discussion and analysis of the hull-propeller interactions. The situation is very similar to attempting the description of railways and automobiles without the concept of the wheel.

With the jet power the configuration efficiency

eta_{EJ} Þ P_E / P_J ,

the jet efficiency

eta_{TJ} Þ P_T / P_J ,

and the pump efficiency of the propeller

eta_{JP} Þ P_J / P_P

may be defined, so that the total propulsive efficiency

eta_{EP} Þ eta_{EJ} eta_{JP}

breaks down into the configuration and pump efficiencies.

As has been shown in many previous papers (see 7.1), these efficiencies are much more meaningful for the evaluation and grading of the hull-propeller and the propeller performance than hull and propeller efficiencies nearly exclusively used up to now.

So far the jet power has not been specified. This can only be done axiomatically, in the present context most conveniently by the 'law'

$$eta_{TJ} = 2 / (1 + (1 + c_T)^{1/2})$$

for the jet efficiency taken from the theory of ideal propellers.

Usually the model of the ideal propeller is tacitly assumed to be the actuator disc and c_T is defined as the thrust loading coefficient

$$c_T \text{ Þ } 2\ T / (rho\ A_P\ V_P{}^2)$$

with the disc area of the propeller

$$A_P = pi\ D^2 / 4\ .$$

As has been shown (Schmiechen, 1978/79) this interpretation is much too narrow, infinitely many models of ideal propellers being imaginable, producing the same 'head'

$$delt\ e \text{ Þ } T / A_P\ .$$

In terms of this generalized view it would be more appropriate to replace the name 'thrust loading coefficient' by 'head coefficient'. Of course 'head' is the traditional jargon for 'increase in energy density'.

This line of interpretation, which has been used for the evaluation of hull-propeller-duct interactions and which can be used for the evaluation of other configurations as well, shall not be followed here, in order not to confuse the essential issues by rather specific details.

Solving the equation for the jet efficiency results in the propeller speed in question

$$V_P = P_J / T - T^2 / (2\ rho\ A_P\ P_J)\ ,$$

the first term representing the average speed at the location of the propeller and the second representing the average speed induced by the propeller.

In practice the normalized equation

$$J_P = K_{PJ} / K_T - 2/pi\ K_T{}^2 / K_{PJ}$$

for the advance ratio of the propeller is solved by iteration and with the solution the speed of the propeller

$$V_P = J_P \; D \; N$$

and all other quantities of interest may be determined.

3.6 Lost Power

As the jet power of the propeller is itself only a purely theoretical quantity, which cannot be measured directly, the problem of propeller speed has not yet been solved but only transformed.

A satisfactory solution requires the generally acceptable axiomatic definition of the hydraulic or pump efficiency of the propeller

$$eta_{JP} \;\text{Þ}\; P_J \;/\; P_P$$

as function of the advance ratio of the propeller, so that the value of the jet power can be determined for every condition.

In order to solve this problem in a way consistent with the exposition so far, the propeller torque has to be known as function of the propeller frequency of revolution and hull speed. As before for the thrust the relationship

$$Q_P = Q_{P0} \; N^2 + Q_{PH} \; N \; V$$

has been used and the parameters have been identified from the set of data described.

As before subsequently the model can be transformed into the normalized format

$$K_{QP} = K_{QP0} + K_{QPH} \; J_H$$

with

$$K_{QP} \;\text{Þ}\; Q_P \;/\; (rho \; D^5 \; N^2) \;,$$

$$K_{QP0} \;\text{Þ}\; Q_{P0} \;/\; (rho \; D^5) \;,$$

$$K_{QPH} \;\text{Þ}\; Q_{PH} \;/\; (rho \; D^4) \;,$$

and the corresponding power ratios

$$K_{PX} \;\text{Þ}\; P_X \;/\; rho \; D^5 \; N^3 \;.$$

For the power ratio of the propeller in particular the relation

$$K_{PP} = 2 \; pi \; K_{QP}$$

is introduced as an axiom. Due to the oscillations of the torque and the frequency of revolution this is in principle not exactly true.

Instead of the pump efficiency the lost power ratio, for short loss ratio,

$$K_{PL} \text{ Þ } K_{PP} - K_{PJ}$$

is being used for the determination of the jet power.

The previously proposed and tried solution, which has been used for the present evaluation as well, is based on the quadratic 'law'

$$K_{PL} = K_{PLP0} + K_{PLP1} J_P + K_{PLP2} J_P^2/2$$

for the loss ratio.

The 'only' problem to be solved is to identify the parameters K_{PLPi} from the already identified parameters K_{T0}, K_{TH}, K_{PP0}, K_{PPH}.

For the solution of this problem the properties of the equivalent open water propeller at the extreme conditions of infinite frequency of revolution and vanishing thrust are utilized (Schmiechen, 1987 a).

The first state, denoted by 0, is by definition a theoretical construct as it cannot be reached physically. At the corresponding bollard test or at acceleration from rest the hull has zero speed.

For the state 0 the jet power is

$$P_{J0} = (2 A_P \text{ rho})^{-1/2} T^{3/2}$$

and consequently the first parameter is

$$K_{PLP0} = K_{PP0} - (2/\text{pi})^{1/2} K_{T0}^{3/2} .$$

Surprisingly these important relations are not used for the evaluation of tugs. The traditionally used ratio of thrust and power is not dimensionless and consequently only of limited use for purposes of grading.

With the axiom of vanishing wake at this state the relation

$$K_{PLP1} = K_{PPH} - (2/\text{pi})^{1/2}\, 3/2\, K_{TO}^{1/2} K_{TH} - K_{T0}/2$$

is obtained for the second parameter.

The last term in this expression results from the linear approximation

$$K_{PJ} = (2/pi)^{1/2} K_T^{3/2} + K_T/2 J_P$$

for the jet power at small advance ratios.

3.7 Zero Thrust

The state of vanishing thrust, denoted by T for towing, is also considered as a theoretical construct, if it is not in the vicinity of the service condition of interest. In the present context it is defined by the condition

$$K_{T0} + K_{TH} J_{HT} = 0 .$$

The loss ratio at this state is obtained from the equation

$$K_{PLT} = K_{PPT} = K_{PP0} + K_{PPH} J_{HT} .$$

From the equation

$$K_{PLP0} + K_{PLP1} J_{PT} + K_{PLP2} J_{PT}^2/2 = K_{PLT}$$

of the corresponding state of the equivalent open water propeller the third parameter of the loss parabola

$$K_{PLP2} = 2 (K_{PLT} - K_{PLP0} - K_{PLP1} J_{PT}) / J_{PT}^2$$

may be determined as soon as the nominal advance ratio of the propeller is known.

Due to the fact, that at the towing state the jet efficiency has unit value, i. e. the jet power vanishes with the thrust, l'Hospital's rule provides

$$J_{PT} = (K_{PPH} - K_{PLHT}) / K_{TH} .$$

With the transformation

$$K_{PLHT} = K_{PLPT} (dJ_P/dJ_H)_T$$

and the relations

$$K_{PLPT} = K_{PLP1} + K_{PLP2} J_{PT}$$

and

$$(dJ_P/dJ_H)_T = - 2/pi K_{TH} / J_{PT}$$

the cubic equation

$$J_{PT} = K_{PPH} / K_{TH} - 2/pi K_{PLP1} / J_{PT} + 4/pi (K_{PLT} - K_{PLP0}) / J_{PT}^2$$

is obtained and to be solved iteratively for the nominal advance ratio of the propeller.

As with the resistance the values of the traditional and rational wakes need not to be the same. But the proposed rational procedure will of course be more acceptable, if the differences are not too large.

From propulsion tests with the model in the VWS deep water towing tank at the hull advance ratio

$$J_H = 0.650$$

the rational wake determined via the equivalent propeller was

$$w = 0.461 .$$

From 'open water tests' at the same frequency of revolution in the small VWS cavitation tunnel, taking into account the tunnel corrections according to Lindgren (1963), the traditional wake

$$w_T = 0.453$$

has been determined via the thrust identity. This value is much higher than the value that would have been obtained from the usual open water results at frequencies of revolution above the critical for open water.

Compared to earlier presentations of the theory a number of simplifications and improvements in the symbols could be introduced due to the assumption of the linear laws for the thrust and torque ratio functions.

Thus the model based on very suggestive conceptions leads to a detailed analysis of the propeller action without reference to the momentum balance. This decoupling of the thrust deduction and wake problems resembles the traditional procedure, as mentioned before.

Abkowitz dispenses for well understood pragmatic reasons with thrust and power measurements and consequently has to adopt axiomatically a law for the thrust ratio as function of the propeller advance ratio. For the identification of all parameters from the momentum balance alone he has to rely on extreme manoeuvres.

The axiomatic laws for the loss ratio, proposed here, or for the thrust ratio, proposed by Abkowitz, as functions of the propeller advance ratio may be 'checked' by the analysis of open water test results (Lazarov and Ivanov, 1989) and plausibly 'explained' by theoretical arguments, but according to their axiomatic nature they cannot be proven.

The whole theory has been developed for rather 'open' propellers, but as has been mentioned before, can be used with none or only small modifications for a wide range of other propulsive arrangements, among others propellers behind asymmetric afterbodies, as in the case of METEOR and its scale model, and for propellers in ducts and tunnels, including ducts partially integrated in the hull (Schmiechen and Goetz, 1989), for which so far no adequate test and analysis techniques have been available (Stiermann, 1984).

3.8 Thrust Deduction Theorem

The decoupling of the identification of thrust deduction and wake does of course not imply that these two interaction phenomena are unrelated. Attempts to clarify this relationship have been made, but were doomed to fail as the following elaboration will show.

For the analysis and discussion of hull-propeller interactions the concept of the equivalent propeller in the energy wake alone, another theoretical construct, not physically realizable, has been exploited (see 7.1).

With the advance speed of this propeller, the energy speed V_E, the energy wake

$$w_E \text{ Þ } (V - V_E) / V \text{ Þ } 1 - V_E / V$$

may be introduced.

Subsequently the expression

$$P_{TE} = T_E V_E / (1 - w_E) = eta_{ETe} P_{Te}$$

is obtained for the effective propeller power with the hull efficiency and the thrust power of the equivalent propeller

$$eta_{ETe} = 1 / (1 - w_E) ,$$

$$P_{Te} = T_E V_E .$$

Further it is postulated that the jet power of the equivalent propeller 'far behind the ship' is equal to that of the propeller:

$$P_{Je} = P_J .$$

With the jet efficiencies

$$eta_{TJ} \text{ Þ } P_T / P_J \text{ Þ } T V_P / P_J,$$

$$eta_{TeJ} \text{ Þ } P_{Te} / P_J$$

the fundamental relationship

$$eta_{EJ} = eta_{ET} eta_{TJ} = eta_{ETe} eta_{TeJ} ,$$

$$(1 - t) eta_{TJ} / (1 - w) = eta_{TeJ} / (1 - w_E)$$

(Schmiechen, 1968) is obtained for the configuration efficiency

$$eta_{EJ} \text{ Þ } P_E / P_J ,$$

leading to the thrust deduction theorem

$$t = (1 + tau + chi) / tau$$
$$- ((1 + tau + chi)^2 - 2 \; tau \; chi)^{1/2} / tau$$

with the notation

$$tau \text{ Þ } (1 + c_T)^{1/2} - 1$$

for the relative speed increase and

$$chi \text{ Þ } V_E / V_P - 1 \text{ Þ } (w - w_E) / (1 - w)$$

for the displacement ratio (Schmiechen, 1968, 1980 a,b). This relation is now also being used in other closely related contexts (Stiermann, 1984).

Thrust deduction and wake fractions having been determined the thrust deduction theorem permits to determine the displacement ratio

$$chi = (t \; (1 + tau) - t^2 \; tau/2) / (1 - t)$$

and subsequently the energy speed and the pressure level

$$p - p_0 = rho \; (V_E^2 - V_P^2) / 2$$

on which the propeller operates.

Due to the fact that the analysis is tradionally not carried that far and, as a consequence of the inconsistency of the data sets it is based upon, cannot be carried that far, the pressure increase due to the displacement flow has so far not been accounted for, e. g. in cavitation tests using grids to simulate the wake.

As scale effects in the wake are primarily concerning the energy wake, it is to be expected that the normalized pressure level

$$C_p \text{ Þ } 2 \; (p - p_0) / rho \; V^2 = (V_E^2 - V_P^2) / V^2$$

at ship and scale model are the same at least in a first approximation. This expectation is confirmed by the results for the METEOR and her model (Figure 34).

The approximation

$$t \sim chi / (1 + tau + chi)$$

of the thrust deduction theorem, valid under the condition

$$2 \tau \chi \ll (1 + \tau + \chi)^2 ,$$

is useful only for some qualitative discussions, but not sufficient for most practical quantitative applications.

3.9 Conclusions

The discussion of the energy balance, another form of the momentum balance, has provided a wealth of insights following the introduction of a number of fundamental concepts. The axiomatic model adopted permits a detailed, adequate description and solution of the problems at hand. Among others some concepts have been clarified and clearly distinguished by names and symbols.

The equality of resistance and towing power at steady towing and the equality of resistance and effective propeller power at steady propulsion, i. e. the balance of demand and supply, is not particularly helpful in understanding propulsion, i. e. the supply.

The equalities mentioned should only be considered after the two components have been clearly identified, e. g. by measurements or some sort of estimation. To put it bluntly, the equations in question can better be solved by pocket calculators than by towing tests.

4. Full scale tests

4.1 Introduction

After the general theory has been developed and discussed as far as necessary, its application on board ships will now be considered. The hull-propeller model being completely identical on model and full scale the focus will have to rest on the identification model, as presented in Figure 2, which accounts for the actual conditions on board.

The important observation is that a closed feed-back loop for the frequency of revolution has to be dealt with, requiring special considerations. The goal of this chapter is, as was that of the previous chapters, to present the problems and solutions proposed in rather general terms, without too many technical details necessary for the actual solution.

4.2 Momentum Balance

If the momentum balance

$$M\ A = T\ (1 - t) + F - R$$

is to be applied to the motions of full scale ships the problems encountered are very different from those on model scale. One reason is that under service conditions in general external forces cannot easily be applied.

The direct consequence is that only in quasisteady tests, i. e. by decelerating and accelerating the ship, the changes of propeller loading necessary for the identification of the parameters can be enforced.

As before, states at the same speed

$$V_1 = V_2 = V$$

are considered at which the mass and the effective resistance remain unchanged:

$$M_1 = M_2 = M\ ,$$

$$R_{E1} = R_{E2} = R_E\ ,$$

the definition of the effective resistance being repeated for ready reference:

$$R_E\ \text{Þ}\ R - F\ .$$

In addition to the value of the inertia M the values of the acceleration and the thrust

$$A_1,\ A_2 \ \text{ and } \ T_1,\ T_2$$

have to be known for the analysis.

The total inertia of the ship consists of its mass, equaling the mass of the displaced water to be determined from the displacement and the density of the water, and the longitudinal hydrodynamic inertia. The latter has been assumed to be three percent of the former.

In view of the difficulty to determine the displacement reliably this was considered to be completely sufficient. In the case of METEOR the displacement was determined on departure for the voyage into the Greenland Sea and the mass was kept constant as far as possible as a routine.

If the values mentioned are known, the identification of the parameters can follow exactly in the same way as on model scale from the momentum balances

$$R_E + T_k/N_k \, V/D \, t_H = T_k - M \, A_k \; : \quad k = 1, 2$$

for two quasisteady states.

The only differences as compared to the model situation discussed in Section 2.5 is that inertial 'forces' take the place of the external forces and that the effective resistance is introduced right from the beginning. The values of the latter and the thrust deduction parameter are the unknowns.

Again it is explicitly stated here that both unknowns are very different in nature. While the effective resistance may assume any value depending on the weather condition met, the thrust deduction parameter is an invariant property of the system.

4.3 State Variables

In order to explain the problems of full scale applications step by step ideal conditions are assumed for a while and it is shown how states of the same speed can be constructed.

If the propeller frequency of revolution is slowly linearly lowered with time and subsequently raised in the same way, as has been done on METEOR all other quantities measured, namely thrust, torque, and speed, are linear functions of time:

$$N = f_{Nk}(t) = N_{0k} + N_{tk} \, t \, ,$$

$$T = f_{Tk}(t) = T_{0k} + T_{tk} \, t \, ,$$

$$Q_P = f_{Qk}(t) = Q_{P0k} + Q_{Ptk} \, t \, ,$$

$$V = f_{Vk}(t) = V_{0k} + V_{tk} \, t \, ,$$

at least in first approximation.

The problem is now to determine the quantities A_1, A_2 and T_1, T_2 from the quantities X_{0k} and X_{tk} assumed given for the moment. The problem of their determination will be discussed in the context of the noisy feed-back loop.

The resulting accelerations are obtained directly without further computation:

$$A_k = dV_k/dt \;\text{Þ}\; V_{tk} \; .$$

For the determination of the other quantities an average speed is chosen and the points in time

$$t_k = (V - V_{0k}) \,/\, V_{tk}$$

are computed and using these, all other quantities in question can be obtained:

$$N_k \;\text{Þ}\; N_{kV} = N_{0k} + N_{tk} \; t_k \; ,$$

$$T_k \;\text{Þ}\; T_{kV} = T_{0k} + T_{tk} \; t_k \; ,$$

$$Q_{Pk} \;\text{Þ}\; Q_{PkV} = Q_{P0k} + Q_{Ptk} \; t_k \; .$$

In this case equal indices do not imply summation. The additional index is necessary in order to distinguish these quantities from those determined later for equal frequency of revolution.

With the values so obtained the values of all other quantities may be determined in exactly the same way explicitly developed before. Due to the inherent extreme sensitivity of the whole procedure mentioned before, data should be evaluated and monitored preferably right after the measurements.

In the same way as states at equal speed states at equal frequency of revolution can be constructed from the same data. The frequency of revolution at the speed selected is defined by the condition of stationarity using the linear interpolation

$$(N - N_{1V}) \,/\, (0 - A_{1V}) = (N_{2V} - N_{1V}) \,/\, (A_{2V} - A_{1V}) \; ,$$

and the corresponding values of speed, thrust, and torque are denoted by

$$V_{1N},\; V_{2N},\; T_{1N},\; T_{2N},\; Q_{P1N},\; Q_{P2N} \; .$$

4.4 Waves, Wind

Contrary to model tests full scale tests usually do not take place in calm water, but under the influence of waves and wind and in general the frequency of revolution is controlled under these circumstances. A schematic overview of the various feed-back loops is shown in Figure 2.

In the terminology of control theory the hull-propeller system to be identified has as its input the frequency of revolution, while its outputs are speed, thrust, and torque. In case of stochastic input and output signals not the signals themselves, but their (cross-)correlations with the input signal have to be used for identification purposes.

If the system to be identified is part of a closed feed-back loop, as is the case here, this procedure leads to systematic errors due to the feed-back of noise. These errors can be avoided only by cross-correlation of all signals with a test signal fed somewhere into the loop, provided the test signal is not correlated with the noise (Solodovnikov, 1963).

This procedure originally developed for linear systems has been generalized for non-linear systems identification (Schmiechen, 1969). In case of a test signal linear with time, i. e. here control of the frequency of revolution as described and applied on board the METEOR, it is sufficient for the suppression of noise to perform correlation with time, extra recording of the test signal not being necessary.

Consequently the equations for the determination of the constants are simply the same as stated before:

$$N_{0k} + t_i N_{tk} = N_i \ ,$$

$$T_{0k} + t_i T_{tk} = T_i \ ,$$

$$Q_{P0k} + t_i Q_{Ptk} = Q_{Pi} \ ,$$

$$V_{0k} + t_i V_{tk} = V_i \ .$$

The values of the data sets

$$t_i,\ N_i,\ T_i,\ Q_{Pi},\ V_i \ : \quad i = 1,.., n$$

need not be instantaneous values, but may be preferably average values over complete shaft revolutions. Optimum estimates of the constants in question are subsequently obtained from the above set of equations.

4.5 Parameters

In practice the two steady states constructed in this way are very close to each other, so that parameter identification requires special considerations.

Introducing estimates of the partial derivatives of the quantities

$$X = T,\ Q_P,\ A$$

with respect to frequency of revolution and speed,

$$X_N \sim (X_{2V} - X_{1V}) / (N_{2V} - N_{1V}) \,,$$

$$X_V \sim (X_{2N} - X_{1N}) / (V_{2N} - V_{1N}) \,,$$

respectively, at each quasisteady state the following two sets of three equations are obtained for the two sets of propeller parameters:

$$\begin{aligned} T_0 \; N^2 + T_H \; N\,V &= T \,, \\ 2\,T_0 \; N + T_H \; V &= T_N \,, \\ T_H \; N &= T_V \end{aligned}$$

and

$$\begin{aligned} Q_{P0} \; N^2 + Q_{PH} \; N\,V &= Q_P \,, \\ 2\,Q_{P0} \; N + Q_{PH} \; V &= Q_{PN} \,, \\ Q_{PH} \; N &= Q_{PV} \,. \end{aligned}$$

If in addition values are available from measurements at service conditions widely apart, as was the case on board the METEOR and usually will be the case, the parameters may be determined in the same way as described before; see 2.6 and 3.6.

The values of the propeller parameters in Table 9.5 have been determined in both ways. At least in the statistical sense exactly the same optimum estimates have been obtained. Of course the individual values from the quasisteady tests exhibited large deviations due to the very severe weather conditions encountered.

A problem of the statistical evaluation was the definition of the set of tests to be taken into consideration. Already at an early stage results of tests disturbed by rudder manoeuvres exceeding the normal rudder activity under control of the auto-pilot or the operation of the stabilizer-fins have been discarded, maybe evaluated at a later stage.

The remaining tests were evaluated in such a way that systematically one test after the other was left out of consideration. If the test left out had a significant influence on the results this test was no longer included in the evaluation. In any particular case the deviation could be traced to some special events noted in the log.

This process of elimination was continued until the results were stable in a statistical sense. In the opinion of the present author this or similar procedures for the separation of random and systematic errors are necessary prerequisites for reliable results.

Of course conventions have to be agreed upon on how to proceed in general and to avoid the impression that matching the expected results is the guiding principle of the process. The strategy described and followed in the case of METEOR is based on the fundamental concepts of the theory of random quantities (v. Mises, 1951) and appears to be adequate for the complex situation at hand and to be the least debatable.

4.6 Uncertainties

While the identification of the propeller parameters can be performed with rather great reliability the situation is not so favorable in case of the thrust deduction parameter. Considerable uncertainties are encountered due to the fact that far apart states cannot be utilized for the identification, the reason being that the unknown resistance is not the same at these states.

The only equation for the identification of the thrust deduction parameter is

$$t_H = D/V\ (T_N - M\ A_N)\ /\ (T_N/N - T/N^2)$$

in any particular case. But due to the fact, that the thrust function and its partial derivative

$$T = T_0\ N^2 + T_H\ N\ V$$

$$T_N = 2\ T_0\ N + T_H\ V$$

can be determined from far apart states, i. e. that the propeller can be 'calibrated' (see 2.6, 3.6, 4.5), the uncertainty can be reduced considerably.

On board the METEOR on the one hand changes in acceleration were usually very small, on the other hand weather conditions were mostly so severe, that the thrust deduction parameter could generally, despite all precautions, not be determined reliably.

Only in one case at rather fine weather and an increased rate of change of the frequency of revolution the signal to noise ratio was large enough for the reliable identification of the thrust deduction parameter. This value has been reported in Table 9.5 and made the basis of the evaluation.

There is of course no problem in future applications, even at bad weather, to provide for a sufficient signal to noise ratio and to perform a statistical evaluation over a number of tests according to equation

$$T_0\ V_i\ t_H\ /\ D = 2\ T_0\ N_i + T_H\ V_i - M\ A_{Ni}\ .$$

Another problem on board the METEOR was the insufficient synchronism of the computer systems resulting in an unsatisfactory determination of the speed. The geographical position of the ship was obtained from the integrated navigation system. With more advanced systems these insufficiencies can of course be easily overcome or rather do not exist.

4.7 Speed over Ground

While the frequency of revolution and the thrust may be measured rather easily, the same is not true for the speed relative to the water, which is governing the propulsive performance. Consequently only state quantities measured at the shaft are used, namely frequency of revolution and thrust.

With the thrust ratio

$$K_T = T / (rho\ D^4\ N^2)$$

the advance ratio

$$J_H = (K_T - K_{T0}) / K_{TH}$$

and the speed relative to the water

$$V = J_H\ D\ N$$

are obtained.

If this speed is different from the speed V_0 over ground measured by other means the drift

$$V_D = V_0 - V$$

of the water may be determined.

The proposal to use the propeller for the measurement of the speed relative to the water is not new. It requires the 'calibration' of the system at a given loading condition in waters known to be free of drift.

In fact this appears to be the only way to obtain reasonable values of the average drift under service conditions, e. g. at heavy sea states. On board the METEOR the oceanographers have been measuring the drift velocities at any depth, but not at the surface.

The 'calibration' of the METEOR was not performed in the way described, but obtained as an average over all service conditions met, i. e. the drift has been considered as a random quantity. In view of the varying courses of the ship required by the oceanographic research program this procedure appeared to be justified and, in view of the sea states met, it appeared to be the only realistic.

4.8 Trial Predictions

With the usual 'continental' method of model testing, the presentation of the results, and performance prediction the analysis of trials presents a problem and needs special conventions.

According to the conceptual frame work developed here this problem does not exist, due to the fact that not the performance at single states, but invariants are determined, which are valid for a wide range of service conditions.

Has a prediction been established on the basis of model tests and have frequency of revolution and torque been measured during the trials, the torque ratio

$$K_{QP}\ \text{Þ}\ Q_P / (\mathrm{rho}\ D^5\ N^2)$$

and all the other quantities may be determined.

In particular the predicted values of speed and thrust

$$V_p = J_H\ D\ N\ ,$$

$$T_p = K_T\ \mathrm{rho}\ D^4\ N^2\ ,$$

can be directly compared with the measured values. In this case the predicted 'calibration' of the ship is checked against a state given by the weather conditions, which happen to prevail at the time of the trials.

Even at considerable deviations of the Froude number and the loading conditions from those of the model tests, no corrections may be necessary as may be concluded from a comparison of the results for the model and the dummy, i. e. the model shortened for simulation of the full scale energy wake; see Tables 9.6 and 9.7.

Scaling and prediction, which are at the focal point of Holtrop's (1978), Nolte's et al. (1989) and Abkowitz's (1990) works, has not yet been treated by the present author. It is felt, that at this stage with only one sample set of results available, it might be too early to embark on general considerations concerning this difficult problem.

4.9 Conclusions

The development of the theory for practical applications of the proposed method on board ships requires special efforts conceptually, theoretically, and numerically due to the feedback of noise, which does not occur in model tests.

All these developments are essentially not new, maybe only in their rigorous application to the identification of propulsive systems and their parameters according to the state of the art, not in hydrodynamics but in systems engineering. From the presentation it should have become evident, that the whole problem of full scale measurements has little, if nothing to do with hydrodynamics.

It is a waste of time and money, if one starts full scale measurements without a conceptual frame work similar to the one proposed in the previous chapters, i. e. the sound top-down approach advocated and developed to a certain state of maturity over the last decade.

5. Test techniques

5.1 Introduction

An essential part of the project was of course the implementation of the measuring technique on board. The original idea was to rely on existing systems, especially those funded by the Ministry of Research and Technology at the Bremer Vulkan ship yard (Nolte et al., 1989) and the Hamburg-Süd shipping company (Grabellus, 1989).

In addition all pertinent problems and the possibilities to employ existing systems have been discussed at great depth with Germanischer Lloyd at Hamburg, CETENA at Genova, and commercial companies.

As a result of these investigations it was found that all systems did not meet the requirements concerning the accuracy and completeness of the measurements. Consequently it was decided to design and implement a new system based on the extensive experience at the Berlin Model Basin.

In this chapter the most important considerations and facts concerning the tests on board the METEOR and with the models will be presented and, in conclusion, the results, presented in Tables 9.5, 9.6 and 9.7 and in Figures 31 bis 36, will be shortly discussed.

5.2 Requirements

The successful propulsion tests with METEOR reported here, had four major objectives:

full scale propulsion tests according to the quasisteady method previously developed in model tests,

particularly including measurement of the thrust,

analysis and evaluation of the results according to the axiomatic theory previously developed for that purpose,

and corresponding model tests.

The propulsion tests were designed to be conducted under a number of very pragmatic constraints in view of future routine applications:

the disturbance of the ship operation were to be marginal, if any,

tests to be possible under all weather conditions,

and as far as possible depend on measuring systems available anyway, the measuring shaft to be certified for permanent installation by Germanischer Lloyd or any other classification society as applicable,

and to provide sufficient information for the complete analysis of hull-propeller interactions and all propulsive efficiencies.

5.3 Solution

The requirements stated have been met as follows:

In the absence of hull towing and propeller open water tests sufficient information for the analysis of hull-propeller interactions can only be obtained from load varying tests.

Without disturbing the operation of the ship these can only be conducted as quasisteady tests, i. e. by small quasisteady changes of the frequency of revolution of the propeller shaft.

In this case inertial 'forces' play the role of external forces, which would be necessary in case of steady testing, but cannot be applied under service conditions.

This concept of quasisteady testing requires the determination of very small accelerations as a consequence of the small changes in frequency of revolution and subsequent small changes of the thrust.

The acceleration can only be obtained by double differentiation of the distance sailed with respect to time. Not only on board the METEOR integrated navigation systems are available for the measurement of the former.

For thrust and torque measurements the intermediate shaft on board the METEOR could partly be replaced by a new hollow shaft, fitted with strain gauges and wireless data transmission and calibrated at the Berlin Model Basin.

Hollow shafts are admitted for permanent installation and have the advantage, that the thrust signals are noticeably higher than at the equivalent solid shaft.

Despite this advantage cross-talk of the torque on the thrust channel is considerable, even if the strain gauges are fitted in the laboratory. Consequently careful calibration is a necessary prerequisite for successful measurements without bias.

5.4 Calibration

The shaft (Figure 3) has in fact been fitted with strain gauges to form a six component balance (Figures 4 and 5) and has been calibrated accordingly including all possible cross-talks in a corresponding loading and measuring rig (Figures 6 to 10).

In designing the calibration rig experience at the Berlin Model Basin with internal loads could be built upon. The hollow shaft and an internal solid shaft were rigidly connected at their one ends and the torque was applied by hydraulically loaded rods between three pairs of levers at their other ends. Thrust was applied simply by three hydraulically loaded rods between the flanges of the hollow shaft.

The total effort going into the calibration rig was quite considerable. The corresponding effort on the computer side, hardware as well as software, was at least of the same order of magnitude. All operations, from checks of the reference load cell, over the calibration of the load rods, to the check of possible influences of the frequency of revolution, have been computer aided.

No serious problems were encountered as all steps had been carefully planned and prepared for, including the 'calibration' of the deflections of the whole systems under loads.

The calibration was based on the linear model

$$L_i - L_{i0} = C_{ij} \, (S_j - S_{j0}) \, ,$$

permitting the loads L_i, i. e. the Cartesian components of the force and the torque, the latter with respect to the center of the measuring shaft, to be determined from the signals S_j by use of the calibration matrix C_{ij}.

The loads themselves are linear functions

$$L_i - L_{i0} = D_{ij} \, (F_j - F_{j0})$$

of the forces F_j in the rods, which have been calibrated including non-linearities.

The problem was the identification of the matrix D_{ij}, being a function of the positions of the rods with respect to the shaft. The actual positions depend not only on the geometry of the rig as measured without loads, but in addition on the deflections under the loads.

Forces in the rods have been applied randomly, roughly corresponding to the loads expected under service conditions, in order to ensure numerically reliable linearisation. The randomness of the loads provided, as a by-product, the non-singularity of the calibration problem, for which a very reliable matrix inversion routine was available. Calibrations in this way took no longer than half an hour, the repeatability of the calibration matrix being very high, even in the less important terms.

As expected the cross-talk of the torque on the thrust signal was the dominant effect observed, but all other terms have been taken into account routinely during the measurements on board by evaluation of the complete matrix product.

5.5 Test Set-up

After calibration the measuring shaft (Figures 11, 12, 13), signal pick-up and conditioning, and data acquisition (Figure 14) were installed in the shaft tunnel on board, so that only digital signals had to be transmitted to the computer system.

On the bridge only the unit for modulation of the frequency of revolution, developed at the Berlin Model Basin, was installed. The HP A400 computer with two terminals and a printer, permitting simple graphical outputs, was located at the drawing room (Figure 15).

While most of the data were transmitted from the shaft, other data, e. g. geographical position and wind data, could be obtained from the data distribution system on board. Problems with the proper synchronization could not be resolved up to the end of the voyage and fewer data were available than expected, e. g. none on the sea state (see 5.6.).

5.6 Test Procedure

The frequency modulated data have been picked up by counters over complete shaft revolutions in order to avoid systematic errors due to truncation of the noisy periodic signals. Apart of the six strain signals four temperature signals have been recorded, the latter via a multiplex channel, finally only at the start of a test as they changed only very slowly.

Usually 256 of such averages over nine complete shaft revolutions were taken during 25.6 minutes, if possible with modulation of the frequency of revolution of about 10 %. Starting from the steady service value the rate of revolution was linearly lowered and subsequently raised in the same way.

Occasionally a number of tests were conducted in direct sequence in order to check the repeatability of the results. Figures 23 to 26 of the physical quantities as functions of time convey an impression of the quality of the data.

During the voyage 72 tests have been made under the various weather conditions and on courses frequently changing due to the oceanographic research program, which was the main purpose of the voyage. Of the 72 tests about 45 could be conducted as described without any major disturbances.

During the other tests e. g. changes of course took place in the test period of about half an hour. Measurements were also taken, when nautical reasons did not permit modulation of the frequency of revolution. Figures 16 to 19 give an impression of the test conditions, Figures 20, 21 and 22 give an overview of the average conditions under which measurements were taken.

Whenever possible zero measurements were taken. With the ship 'at rest' and the turning machine in operation measurements have been taken repeatedly over complete revolutions and averaged. The repeatability of these zeros was better than 1% of the typical values over the whole voyage, even for the thrust.

The values obtained were taken as zero values for the determination of all physical quantities including the torque. For lack of data no dependence of the frictional torque of the bearings on the frequency of revolution has been accounted for.

The repeatability of the results for tests following each other without delay, i. e. without changes of the propulsive conditions, was extremely good as data reduction and analysis right after the tests showed. Differences in the results could consequently be attributed to external causes, the parameters of which were only incompletely measured on board the METEOR, as has been mentioned before.

The idea of Grabellus (1989) to measure the 'vertical' acceleration of the foreship and use this at least as a crude measure for the sea state came to the attention of the author only after the voyage. The attempt to utilize the same idea and derive some information about the sea state from the standard deviations of the signals picked up at the shaft was not successful due to the extreme filtering applied.

On board the METEOR a system of programs for data reduction and evaluation was developed and used with some success. So first results could be presented at the STG Special Meeting at Berne, the STG Summer Meeting at Berlin, and the BMFT Status Seminar at Hamburg (Schmiechen, 1989). All the results are superceeded by those of the final evaluation presented here.

5.7 Model Tests

At HSVA and VWS a large number of model tests have been carried out, including especially load varying tests, of which only the facts and results of interest in this context will be reported.

The model was built at HSVA according to drawings, which were available from an earlier project (HSVA-model Nr. 3398-1001; VWS-model Nr. 2545.0). It was built in two parts of wood to scale 1 : 14.5 (Figures 27 and 28).

In addition a shorter foreship was built according to design and drawing of VWS (VWS-model Nr. 2545.1, Figure 29). The data of METEOR, the model, and the dummy are collated in Table 9.1. Further data of ship and propeller are to be found in Table 9.2.

The drafts of METEOR before leaving Hamburg harbour were 5.34 m at the forward and 5.54 m at the aft perpendicular at the density rho = 1.0001 t/m^3. This diplacement corresponds to the drafts of 4.78 m at the forward and 4.98 m at the aft perpendicular in the North Sea at the density rho = 1.028 t/m^3.

At this loading condition the model was investigated at HSVA and VWS. For turbulence stimulation a sand strip of 60 mm width was fitted at station 9.75. The model propeller was manufactured at VWS according to a HSVA drawing (VWS-Propeller Nr. 1419).

Tables 9.3 and 9.4 contain the test results at HSVA as well as the results of the traditional evaluation. The test results are also plotted in Figure 30, together with the results of the load varying tests at the lowest and highest Froude number investigated. The results have already been discussed in Section 2.6.

The tests have been carried out in the large towing tank of HSVA and the evaluation was made according to the standard correlation method of HSVA. Details of the procedure are part of the HSVA report (Zerbst and Keil, 1989), but are not of interest here.

Very similar tests have been carried out in the large towing tank of VWS. Load varying tests were conducted at much larger load variations in order to cover a wider range of propulsive conditions. Only the results of two tests at the highest Froude number investigated at VWS, F_N = 0.2165, have been evaluated.

As described before, the two steady states, on which the evaluation has been based, have been constructed from the instantaneous values measured. The reason for the unsteadiness of most of the states was to be attributed to control of the model speed via the frequency of revolution. Additional tests showed, that even when the frequency of revolution was kept constant, no completely steady conditions were obtained.

The tests with the dummy (fore)ship shortened according to Rader (1976) have been carried out and evaluated in the same way as those with the original scale model. At the high speed of interest the heavy trim of the dummy caused considerable problems. Results are reported in Table 9.7, but have not been plotted in Figures 31 to 36. In view of the problems mentioned and the additonal costs dummy models are not recommendable for the type of testing proposed.

5.8 Test Results

The results obtained according to the method developed for METEOR, the model (2545.0), and the dummy (2545.1) are given in Tables 9.5, 9.6 and 9.7. The results for METEOR and the model (2545.0) are also shown in Figures 31 to 36 for direct comparison. Some observations may be noted here.

Thrust- and torque ratios (Figure 31): For the state of hull and propeller of METEOR in November 1988 in mostly heavy weather in the Greenland Sea the thrust ratio as function of the hull advance ratio was nearly identical with that of the model at Froude number .2165 in the calm water of the VWS towing tank.

Loss parabolas, wake fractions (Figure 32): The loss parabolas constructed from thrust and torque ratios for METEOR and its model are nearly identical in the range of interest, while the wake fractions determined accordingly differ considerably as expected due to scale effects at the model hull.

Propeller efficiencies (Figure 33): While pump efficiencies of the propellers of METEOR and the model are very nearly the same the jet efficiencies and the propulsion efficiencies exhibit differences due to differences in thrust loading coefficients, which are not themselves scale effects, but consequences of them.

Thrust deduction fractions (Figure 34): The differences in thrust deduction fractions of METEOR and the model are of the same order of magnitude as to be expected from earlier tests with and without boundary layer suction and from simple theoretical considerations based on the thrust deduction theorem. The pressure ratios of METEOR and the model are very nearly equal, due to the fact that the displacement wakes are nearly equal on full and model scale. Scale effects are in first approximation only concerning the energy wake.

Hull efficiencies (Figure 35): Of interest are not the well known differences in the hull efficiencies but the fact, that the coefficients of the effective thrust differ only very little. The prediction of these small differences is most important for the reliable prediction of the frequency of revolution.

Total efficiencies (Figure 36): As most other quantities the configuration and propulsive efficiencies for METEOR and the model do not differ very much, i. e. all scale effects cancel concerning these quantities. This fact has always been suspected to be the reason for the success of the traditional prediction procedure.

It may again be stated explicitly that all results for the wide range of conditions have been derived, according to very simple rules, from only five parameters identified from only two steady states. From the presentation it should have become evident that the results obtained in the way described are much closer to physics of interaction than those obtained in the traditional way.

5.9 Conclusions

The measuring and test technique on board and on model scale do not pose any problems in principle. The quality of the results depends solely on sound and careful 'craftsmanship' in the coherent solution of the very large number of very different, but closely interlinked problems.

The results reported are the most 'likely' and not yet the most probable in the sense of the theory of probability, although at any stage of the evaluation statistical methods have been consistently employed. As has been stressed again and again problems of methodology and systematic errors have still been of primary concern at the present state of development.

It has also been mentioned that before the necessary standardization of the method a number of principal questions have to be clarified and answered. Only after that meaningful statistical quality control is possible.

6. Conclusions

6.1 Review

The proposed technique proved to be adequate in every respect: in particular the measuring technique including all the details and the technique of systems identification under service conditions by correlation with the test signal, i. e. time in case of linear changes of the frequency of revolutions. For practical applications the simplifications of the thrust deduction axiom and the model test technique are the major break-throughs.

The basis is a simple, explicit, and coherent axiomatic model with the minimum number of five parameters, sufficient for the description of the propulsive performance of ships with unducted fixed pitch propellers in a wide range of service conditions.

The five parameters in question, i. e. the propulsive properties of the ship defined by the axiomatic model, may be identified in principle simply from only two steady states of propulsion.

On board ships these two states can be constructed by means of statistical methods from data obtained during quasisteady de- and acceleration at the service condition under investigation without disturbing the ship operation. Of course a sufficient signal to noise ratio has to be maintained.

On model scale the two different states can simply be enforced by the application of two different external forces. Even under the rather ideal conditions in towing tanks special care has to be taken to establish truly stationary conditions or to construct such conditions from the data at hand.

A 'drawback' of the method is, that it requires not only measurements of the torque but the thrust as well. If this requirement is dropped, as e. g. Abkowitz does, one loses the possibility of a complete analysis in terms of data taken only in the vicinity of the service condition.

In practice measuring shafts and their calibration are necessary for torque and thrust only. The measurement of speed needs to be much better than on METEOR, in order to permit a reliable determination of the acceleration.

The data are presently being analyzed in another project and are available any time for further analysis. For the first time not only full scale data, but the corresponding model data obtained in the same way can be presented. Of course many sets of data of the same kind are in urgent need. Practitioners should note, that a tool is available now to obtain these data and that this tool should be used now.

The results will hopefully convince theorists, that the new paradigm for the research into hull-propeller interaction can be the solid basis for concerted, large scale activities in that field. The state of the art is already very advanced although few researchers contributed so far.

The problems of error analysis and quality control have been taken into account during the whole project. But up to the final evaluation systematic errors proved to pose the overriding problems due to the extreme inherent sensitivity of Froude's scheme of analysis. In most cases appropriate sets had to be constructed before statistical methods could be applied to them.

With the successful tests on board the METEOR and the results presented here the continuous efforts of the present author to rationalize the theory of hull-propeller interaction and their applications have reached a certain end. But this is only the basis for further scientific and industrial developments to be undertaken by joint forces.

6.2 Assessment

It is not possible to estimate the economic advantages to be gained by the new innovative paradigm or only assess the consequences in technology as rationalizations will take place wherever possible. Prospects have to be judged in the context of scenarios of the future.

Already today model tests performed according to the method proposed are not only cheaper, but their results are much more informative as compared to those of the traditional tests. This has already been expected in a discussion at an early stage of the development; see discussions of Schmiechen (1980).

Even the effects on model testing may only be guessed. In many cases with non-traditional afterbodies, as e. g. asymmetric afterbodies and those of vessels for inland navigation, the new method will eventually be the only one to be applied, maybe in combination with boundary layer suction for the simulation of the full scale propeller inflow. Further applications as e. g. at ice breakers and high speed crafts have been mentioned in the report.

As soon as more results from full scale ships will be available corresponding model tests will be asked for more frequently. As experience in other fields shows a more physical evaluation offers advantages over a traditional evaluation.

In view of the application on board ships the method opens the possibilities for continuous monitoring of the propulsion conditions, e. g. for optimizing the docking intervals, and for the research into the scale effects and the influence of various parameters.

Research itself will be re-directed to other problems leading hopefully to a more meaningful and efficient use of limited resources. Many old problems appear to be pseudo-problems in the light of the new framework or should at least be treated in a new way.

Teaching will be drastically rationalized by the theory proposed. The advantage gained can hardly be over-estimated. Rationalization starts with the conceptual framework of the next generation.

A certain confidence in the assessment of the future development outlined is based on the knowledge of the theory and history of science. Typical, widely known examples of successful axiomatizations and their consequences are Euclidean geometry, Newtonian mechanics, probability theory, and, still more recent, the rational mechanics of continua.

The procedure followed thus corresponds to the state of the art in other fields and tries to satisfy what is felt to be an urgent demand in the theory of ships. As a matter of fact the theory of ships, which deserves this name, has been neglected by universities over decades in favor of other, more fashionable topics. Appreciable work has been done at partial aspects, but the overall picture, guiding our strategies and actions, got lost.

Of course it may be asked now what all these long range benefits have to do with the project reported and its direct success. The goal was to do the last step in a very long extensive development in the evaluation of the propulsive performance of ships and this step has been completed successfully.

More specifically the goal was to try the method proposed on board a ship and do the preliminary steps towards a routine industrial application. It is certain that not all ships will be fitted right-away with the corresponding hard- and software, but there is a sufficient number of cases, where such systems would be used, if they already existed.

6.3 Prospects

In this short report some future prospects and projects could only be mentioned as e. g. model testing, ship trials, service monitoring. Fantasy should not be limited when designing the scenarios for the future. It should be kept in mind though, that any individual application will require its own development.

At present the integration of the method into an existing ship control system (Harms, 1990) is under consideration. The next step will be the remote parameter identification and monitoring of the propulsion of a ship.

For future applications of the method in model tests and ship trials a special expert system will be of great help. Its development appears possible on the basis of the present experience but could not be realized during the project due to the constraints in time and funds.

Results presented at the Ice Session of the 19th ITTC (1990) suggest, that model tests in ice can be drastically rationalized and at the same time the quality of their results increased by an order of magnitude. The application on board ice breakers will for the first time provide reliable values of the resistance under service conditions. Projects for the development and trial of the techniques are promising and will be carried out in cooperation with the Hamburg Ship Model Basin.

The application of the method to ducted propellers is possible with only minor additions, as has been mentioned earlier. The application to adjustable pitch propellers will of course require major extensions of the axiomatic models, not only due to the additional control variable, but due to much wider range of operation to be covered.

The consequence will be that more than five parameters will have to be taken into account. If the generalization is carried out according to the pattern set, the necessary effort will still be very limited. As the results obtained are of great importance for the control of adjustable pitch propellers, talks have been taken up to initiate the corresponding development.

In general the present paper is a contribution to bridge the gap between naval architects and marine engineers, resulting from the different problems they have to solve. In the light of the present presentation the gap does not exist, but appears to be a pseudo-problem resulting from misconceptions on the mechanism of propulsion, which may be understood as a balance of demand and supply.

The problem of design of propellers is influenced by these ideas as well (Schmiechen, 1983). In pursuit of work on the design of optimal wake adapted ducted propellers (Schmiechen and Zhou, 1987/88) a pumpstage is being designed to meet given design requirements, and the total hull-propeller system will be tested using the procedure described as the only one available.

As the proposed method is much closer to physics than the traditional one and, as has been stated over and over again, applicable not only on model scale, validation of CFD-codes, developed for future application in ship design, may eventually only be achieved by the method proposed, maybe including additional local measurements if absolutely necessary.

In addition universities may find a large number of promising research projects as have been outlined in the paper. Particularly important are the fundamental problems of quality assurance in the face of systematic and random errors.

Numerous presentations and discussions have raised worldwide interest in the ideas proposed and they have been subject of a first international workshop at VWS, the Berlin Model Basin, in September 1988. The 2nd International Workshop on the Rational Theory of Hull-Propeller Interaction (2nd INTERACTION Berlin '91) will be held in cooperation with the Powering Performance Committee of the 20th ITTC on June 13 and 14, 1991 at the Berlin Model Basin.

6.4 Thanks

Thanks are due in the first place to Regierungsdirektor J. Leinweber of the Federal Ministry for Research and Technology (BMFT), who supported the project and could provide the necessary funds.

The success of the project is due to the joint efforts of many colleagues at VWS, the Berlin Model Basin, in particular Werner Müller, Lothar Hahn, Karl Meissner, Manfred Lange, Herbert Strube, Dietmar Hinsche, Yan Xiao-bo and Ulrich Schwer, who with great engagement in the design office, the workshops, at the computers, in the labs, and, last but not least, on board the METEOR helped to guarantee the quality of the measurements.

Special thanks are due to Captain H. Bruns, his crew, and the scientific management of the METEOR for the efficient cooperation and support during the preparation and the actual trials on board.

7. References

7.1 Basic Work

Schmiechen, M.: Performance Criteria for Pulse-Jet Propellers. Proc. 7th Symp. Nav. Hyd. (Rome, 1968) pp. 1085/ 1104.

Schmiechen, M.: Design and Evaluation of Experiments for the Identification of Physical Systems. MIT/NAME Report 69-1, Cambridge, Mass. 1969.

Schmiechen, M.: Über die Bewertung hydromechanischer Propulsionssysteme. Schiffstechnik 17 (1970) No. 89, pp. 91/ 94.

Schmiechen, M.: On State Space Models and Their Application to Hydromechanic Systems. NAUT Report 5002, Tokyo 1973.

Schmiechen, M.: Rationale Modelle idealer Propeller endlicher Belastung. Schiffstechnik 25 (1978) No. 121, pp. 113/120. Discussion by J. A. Sparenberg: Schiffstechnik 26 (1979) No. 2, pp. 117/121.

Schmiechen, M.: Eine axiomatische Theorie der Wechselwirkungen zwischen Schiffsrumpf und -propeller. Fritz Horn zum 100. Geburtstag gewidmet. Schiffstechnik 27 (1980) No. 2, pp. 67/99.

Schmiechen, M.: Nachstrom und Sog aus Propulsionsversuchen allein. Eine rationale Theorie der Wechselwirkungen zwischen Schiffsrumpf und -propeller. Jb. STG 74 (1980) pp. 333/351.

Schmiechen, M.: Über Weiterentwicklungen des Vorschlages "Nachstrom und Sog aus Propulsionsversuchen allein". Schiff & Hafen 34 (1982) No. 1, pp. 91/92.

Schmiechen, M.: On Optimal Ducted Propellers for Bodies of Revolution - A Speculative Reconstruction. Proc. Internat. Symp. on Ship Hydrodynamics and Energy Saving (El Pardo, 1983) Nr. VI, 2, pp. 1/7.

Schmiechen, M.: Wake and Thrust Deduction from Propulsion Tests Alone. A Rational Theory of Ship Hull-Propeller Interaction. Proc. 15th Symp. Nav. Hyd. (1984) pp. 481/500.

Schmiechen, M.: Schiffsmodellversuche mit Grenzschichtbeeinflussung durch Absaugung. VWS-Bericht Nr. 1021/85; FDS-Bericht Nr. 163/1985.

Schmiechen, M.: Ship Model Tests with Boundary Layer Suction. VWS Report No. 1071/86.

Schmiechen, M. and Zhou Lian-di: An Advanced Method for the Design of Optimal Ducted Propellers behind Bodies of Revolution. VWS Report No. 1083/1987; Final report on a Partnership in Engineering Sciences Sponsored by Stiftung

Volkswagenwerk.

Schmiechen, M.: Wake and Thrust Deduction from Quasisteady Ship Model Propulsion Tests Alone. VWS Report No. 1100/87. Published on occasion of a visit to Korean and Japanese ship research institutes and the 18th ITTC at Kobe in October 1987 and in commemoration of the 4th ITTC at Berlin in May 1937.

Schmiechen, M.: Ermittlung von Nachstrom und Sog aus quasistationären Propulsionsversuchen allein. VWS-Bericht Nr. 1105/88; FDS-Bericht Nr. 194/1988.

Schmiechen, M. and Zhou Lian-di: An Advanced Method for Design of Optimal Ducted Propellers behind Bodies of Revolution. Proc. SNAME Spring Meeting (1988) pp. 29/39. 13th STAR Symp. and 3rd. IMSD Conf. (Pittsburgh, June 8 - 10, 1988).

Schmiechen, M. and V. Goetz: Propeller in Düsen und Tunneln. VWS-Bericht Nr. 1144/89; BMFT-Bericht.

Schmiechen, M.: Quasistationäre Propulsionsversuche mit der METEOR. STG-Sprechtag: Betriebsmessungen an Bord (Berne, 15. März 1989). Jb. STG 83 (1989) p. 56.

Schmiechen, M.: Quasistationäre Propulsionsversuche mit der METEOR. STG Sommertagung Berlin, 16. Mai 1989. Jb. STG 83 (1989) pp. 120/126.

Schmiechen, M.: Quasistationäre Propulsionsversuche mit der METEOR. In: Germanischer Lloyd (Herausgeber): Entwicklungen in der Schiffstechnik, BMFT-Statusseminar (Hamburg, 1989). Köln: TÜV Rheinland, 1989, pp. 87/105.

Schmiechen, M.: Die Methode der quasistationären Propulsion und ihre Erprobung an Bord der METEOR. VWS-Bericht Nr. 1180/90; BMFT-Bericht.

7.2 Other Sources

Abkowitz, M. A. and Liu Geng-shen: Measurement of Ship Resistance, Powering and Manoeuvering Coefficients from Simple Trials during a Regular Voyage. Proc. SNAME 96 (1988) pp. 97/128.

Abkowitz, M. A.: The Use of System Identification Techniques to Measure the Ship Resistance, Powering and Manoeuvering Coefficients of the Exxon Philadelphia and a Submarine from Simple Trials during a Routine Voyage. Proc. 15th ATTC (St. John's, 1989).

Abkowitz, M. A.: Full Scale Measurements of the Resistance and Powering Coefficients and the Resulting Improvement in the Extrapolation from Model to Ship. Proc. 19th ITTC (Madrid, 1990).

Blendermann, W.: Die Windkräfte am Schiff. Geschätzte Windlastbeiwerte für ein Forschungsschiff. IfS-Bericht Nr. 467, 1986.

Carnap, R.: Introduction to Symbolic Logic and Its Applications. New York: Dover Publications, 1958.

Ferrando, M. and C. Podenzana-Bonvino: A Short Review of Full Scale Tests. 19th ITTC (Madrid, 1990). Written contribution.

Froude, R. E.: A Description of a Method of Investigation of Screw-Propeller Efficiency. Proc. INA 24 (1883) pp. 231/255.

Grabellus, W.: Bordmessungen des Leistungsbedarfs und Fahrtoptimierung eines Containerschiffes. Dissertation TU Berlin, 1989.

Grigson, C. W. B.: On Predicting the Performance of Ships from Models. RINA 126 (1984) pp. 125/139.

Grigson, C. W. B.: The Ocean Trials of a Large Merchantman in Ballast and Their Correlation with Model Data. RINA 130 (1988) pp. 85/106.

Grigson, C. W. B.: An Absolute Determination of the Performance of a Slender Merchantman. RINA 132 (1990). Preprint.

Grigson, C. W. B.: Screws Working in Behind and the Prediction of the Performance of Full Ships. Private communication.

Grothues-Spork, H.: On Geosim Tests for the Research Vessel "Meteor" and a Tanker. Trans. Inst. of Mar. Eng's 77 (1965) No. 10, pp. 259/278. (The "Meteor" was the predecessor of the METEOR investigated!)

Gunsteren, van, L. A.: A Contribution to the Solution of Some Specific Ship Propulsion Problems - A Reappraisal of Momentum

Theory. Dissertation TH Delft, 1973.

Harms, D.: Geamar 100 ISL - Ein integriertes Automationssystem für die ganze Schiffsführung. STG Sprechtag: Integrierte Automationssysteme an Bord (Travemünde, 18. September 1990). Jb. STG 85 (1990). Preprint.

Harvald, Sv. Aa.: Prediction of Power of Ships. Lecture Notes, TH Lyngby, 1977.

Harvald, Sv. Aa.: Comments to the Report of the Performance Committee: Remarks Regarding the Form Factor. Denmark. Proc. 17th ITTC (Leningrad, 1984).

Harvald, Sv. Aa.: Resistance and Propulsion of Ships. New York: John Wiley and Sons, 1983.

Harvald, Sv. Aa. and J. M. Hee: The Components of the Propulsive Efficiency of Ships in Relation to the Design Procedure. Proc. SNAME Spring Meeting (1988) pp. 29/39. 13th STAR Symp. and 3rd IMSD Conf. (Pittsburgh, June 08-10, 1988). Discussion by H. Langenberg.

Herzer, R.: Das 8-DMS-Verfahren, ein Verfahren zur Messung des Propellerschubes auf Schiffen. ATM (1965) V 132-22.

Holtrop, J.: Power Prediction by a Modern Analysis Method without Resistance and Open-Water Tests. NSMB Report W11006-19-VT, 1978.

Holtrop, J.: Quasi-Steady Model Propulsion Testing - First Results. MARIN Report Nr. 50604-3-VT, 1986.

Holtrop, J.: Are Model Resistance Tests Indispensable? Proc. 19th ITTC (1990). Group Discussion on New Facilities and New Analysis Methods, Invited Paper. Discussion by J. W. English.

Huang, T. T. and N. C. Groves: Effective Wake: Theory and Experiments. Proc. 13th Symp. Nav. Hyd. (Tokyo, 1980) pp. 651/673.

Proc. 18th ITTC (International Towing Tank Conference), Kobe 1987. Volume 1, 1987; Volume 2, 1988.

Proc. 19th ITTC (International Towing Tank Conference), Madrid 1990. Volume 1, 1990; Standard Symbols and Terminology, Draft 1990; Written Contributions.

Jinnaka, T.: Errors in Self-Propulsion Tests due to Acceleration of Model Ship. Proc. 18th ITTC (Rome, 1969). Contribution to Performance Session.

Keil, U.: Fortschritt in der Prognosegenauigkeit durch neue Versuchstechnik beim Propulsionsversuch. HANSA 119 (1982) No. 18, pp. 1119/1120.

Kux, J. and H. Söding: Möglichkeiten und Grenzen der Berechnung turbulenter Schiffsumströmungen. Jb. STG 85 (1990). Preprint.

Laudan, J. and P. Oltmann: Strömungsbeeinflussung durch Asymmetrie. HSVA Bericht Nr. 1561, 1988.

Lazarov, S. and I. Ivanov: Investigation of Schmiechen's Method for Determination of Wake and Thrust Deduction from Self-Propulsion Tests Alone. BSHC Report, 1989. English version of the main part.

Lindgren, H.: Propeller Cavitation Experiment in Uniform Flow. A Note on Test Procedure, Corrections and Presentation. Proc. 10th ITTC (Teddington, 1963) Vol.1, Report of Performance Committee, Appendix 1.

Meyne, K.: Untersuchung der Propellergrenzschichtströmung und der Einfluß der Reibung auf die Propellerkenngrößen. Jb. STG 66 (1972) pp. 317/399.

Mildner, F.: Vergleichende Untersuchung von Verfahren zur experimentellen Bestimmung des Schiffspropellerschubes. VWS Bericht Nr. 630/73.

Mildner, F.: Untersuchung über die Genauigkeit verschiedener Meßverfahren zur Bestimmung der effektiven Wellenleistung. VWS Bericht Nr. 666/73.

Mildner, F.: Über die Bestimmung des Propellerschubes mit Dehnungsmeßstreifen. Dissertation TU Berlin, 1973.

Mises, v., R.: Wahrscheinlichkeit, Statistik und Wahrheit. Wien: Springer-Verlag, 1951. 3. Edition.

N.N.: Propeller-Thrust Measurement. MARIN Report 1987, No.27, pp. 306.

Nakatake, K. and R. Yamazaki: Free Surface Effect on Hull-Propeller-Rudder Interactions. Proc. 12th Symp. Nav. Hyd. (Hamburg, 1980) pp. 463/476.

Nolte, A., H. Sendner and G. Szczesnowski: Messung von Leistung, Schub und Schiffsgeschwindigkeit zur Kontrolle des Propulsionswirkungsgrades. Jb. STG 83 (1989) pp. 61/68.

Nolte, A.: Experimentelle Bestimmung der effektiven Nachstromziffer in Modell und Großausführung. STG-Sprechtag: Propeller und Kavitation (Hamburg, 28. Juni 1990). Jb. STG 84 (1990). Preprint.

Rader, H.: Die Bedeutung des Nachstroms für die Wechselwirkungen zwischen Schiffsrumpf und Propeller. 11. Fortbildungskurs am Institut für Schiffbau, Hamburg, 1976.

Schuster, S., H. Grothues-Spork, H. Thieme, H. Schwanecke and K. Wieghardt: Meteor-Meßfahrten. Jb. STG 62 (1967) pp. 159/204.

Solodovnikov, W. W.: Einführung in die statistische Dynamik linearer Regelungssysteme. München: R. Oldenbourg Verlag, 1963.

Stiermann, E. J.: Extrapolation Methods for Ships Fitted with a Ducted Propeller. ISP 31 (1984) No. 356, pp.80/87.

Tanaka, H.: Some Experiences of Model Tests for SWATH Model at SRI. Memorandum for the 1st Meeting of the 18th ITTC HSMVC, March 18, 1985.

Trincas, G. and M. Spitoni: Hydrodynamic Evaluation in Preliminary Design of Asymmetric High Block Ships. ISKP 4/89.

Yamasaki, T. and T. Tsuda: Accuracies Ensured by Towing Tank Tests. Transl. from Proc. JTTC Symposium 1983.

Zerbst, J. and U. Keil: Modellversuche für das Forschungsschiff Meteor. HSVA Bericht Nr. WP 26, 1989.

8. Symbols

8.1 Remarks

'Quantities', i. e. concepts, corresponding to certain physical aspects of objects in the world surrounding us, are called by names and denoted by symbols. As may happen with names they may for one or the other reason be completely misleading. This is particularly true for the name 'quantities' given to aspects of physical objects, i. e. qualities, which we want to refer to in the first place.

Even worse is the use of the name 'variable' for an aspect of a physical object. The reason for this jargon is of course that the values of an aspect may vary in time, as e. g. that of the resistance.

Evidently the various concepts of resistance remained constant during the exposition and they are consequently denoted by constants, so-called functor constants (Carnap, 1958). These functor constants denote different operational, eventually standardized interpretations of the concepts.

As usual in technical writing the same sign is used here to denote the number variable (the only variable) for the values of the aspect in question and with additional indices individual constant values, e. g. in SI units. In many cases this rather sloppy notational convention is leading to unbearable confusion and separate symbols have to be assigned to the constant functions, the variables of their values, and individual values.

In some cases names and symbols for concepts used in earlier publications have been further updated in the present exposition in the light of new insights in order to call things by their 'right' names. The goal in the long range is of course to arrive at internationally accepted symbols as adequate as possible and consequently lasting. Some principles to this end have been formulated in the Preface to the ITTC List of Standard Symbols (19th ITTC, 1990).

To call things by their 'right' names is by no means a trivial or academic problem, but a necessary prerequisite of efficient research and teaching far too long neglected by the academic community world-wide. The losses, financial and ideal, due to inadequate language and notation can hardly be overestimated. And there is no excuse for misleading and frustrating young people.

What follows is a rather complete list of all symbols used together with an indication, where they have first been introduced. In previous publications quantities and indices have been listed separately and rules for the formation of symbols have been stated explicitly. But the acceptance of this very efficient system was pretty poor, at least so far.

Examples are the powers P_X, P_Y and P_Z and the efficiencies or factors of merit

$$eta_{XY} \text{ Þ } P_X / P_Y$$

with the rule of combination

$$eta_{XY}\ eta_{YZ} \text{ Þ } eta_{XZ}$$

and the indices

$$X, Y, Z = (R, F, E, T, J, P) .$$

Similar rules may be derived e. g. for the derivatives

$$X_{YZiS} \text{ Þ } (d^i X_Y / dJ_Z{}^i)_S$$

of the quantities X_Y of hull or propeller

$$Z = (H, P)$$

at vanishing thrust or speed

$$S = (0, T) .$$

As usual in technical writing they are not explicitly introduced.

In the list of symbols the following items will be found under

Name: the names of the concepts, i. e. of the qualities or aspects of the objects hull and propeller;

Section: the section in which the concept is introduced, as basic or derived, together with its name and symbol;

Symbol: the symbols for the concepts or qualities, i. e. the functor constants, at the same time symbols for the corresponding number variables for values of their quantities in SI units, and sometimes symbols for individual values of the quantities;

ITTC: the ITTC Standard Symbols, as far as defined up to now.

8.2 List

ITTC	Symbol	Section	Name
a	A	2.2	acceleration of the hull
A_D	A_P	3.5	disc area of the propeller
	chi	3.8	displacement influence ratio
c_{Th}	c_T	3.5	thrust coefficient of the propeller
	C_E	2.6	coefficient of the effective propeller thrust
	C_{ij}	5.4	calibration matrix
	C_p	3.8	pressure ratio
	C_R	2.6	coefficient of the effective hull resistance
D	D	2.4	diameter of the propeller
	D_{ij}	5.4	calibration configuration matrix
E	E_k	3.2	kinetic energy of the ship
	eta_{EJ}	3.5	hull-propeller configuration factor of merit
eta_D	eta_{EP}	3.3	propulsive efficiency
eta_H	eta_{ET}	3.3	hull efficiency
	eta_{ETe}	3.8	hull efficiency of the equivalent propeller in the energy wake
	eta_{JP}	3.5	pump efficiency of the propeller, propeller factor of merit
eta_I	eta_{TJ}	3.5	jet efficiency of the propeller, ideal propeller efficiency
	eta_{TeJ}	3.8	jet efficiency of the equivalent propeller

			in the energy wake
eta_B	eta_{TP}	3.3	propulsive efficiency of the propeller, propeller efficiency
	f_{QP}	3.4	non-dimensional torque function of the propeller in open water
	f_{TP}	3.4	non-dimensional thrust function of the propeller in open water
F	F	2.2	resulting external force at the hull
	F_i	5.4	towing forces
F_n	F_N		Froude number
J_A	J_H	2.4	advance ratio of the hull
	J_{HT}	3.7	nominal advance ratio of the hull
J	J_P	3.4	advance ratio of the propeller
	J_{PT}	3.7	nominal advance ratio of the propeller
	K_{PJ}	3.5	jet power ratio of the propeller
	K_{PL}	3.6	lost power ratio of the propeller
	K_{PP}	3.6	power ratio of the propeller
	K_{PX}	3.6	power ratios
	K_{QL}	3.6	lost torque ratio of the propeller
K_Q	K_{QP}	3.4	torque ratio of the propeller
	K_{QP0}	3.6	non-dimensional torque parameter
	K_{QPH}	3.6	non-dimensional torque parameter
K_T	K_T	2.6	thrust ratio of the propeller

	K_{T0}	2.6	non-dimensional thrust parameter
	K_{TH}	2.6	non-dimensional thrust parameter
	L_i	5.4	loads
m	m	2.2	mass of the ship
m_x	m_X	2.2	hydrodynamic longitudinal inertia of the ship
	M	2.2	total longitudinal mass or inertia of the ship
n	N	2.2	frequency of revolution of the propeller
	omeg	2.4	wake parameter
	p	3.8	pressure
	p_0	3.8	reference pressure
	pi		3.14159...
P_E	P_E	3.2	effective power of the propeller
	P_F	3.2	power of the resulting external force, e. g. towing power
	P_J	3.5	jet power of the propeller
	P_{Je}	3.8	jet power of the equivalent propeller in the energy wake
	P_{J0}	3.6	jet power of the propeller at vanishing advance ratio
P_D	P_P	3.3	shaft power of the propeller
	P_R	3.2	power of the resistance
P_T	P_T	3.3	thrust power of the propeller
	P_{Te}	3.8	thrust power of the equivalent propeller in the energy wake
P	P_X	3.6	power in general

Q	Q_P	2.2	torque of the propeller
	Q_{P0}	3.6	torque parameter
	Q_{PH}	3.6	torque parameter
	rho	2.6	density of the water
	R	2.2	resulting resistance of the hull with appendages
	R_E	2.5	effective resistance of the hull with appendages
R_n	R_N		Reynolds number
R_T	R_T	2.3	resistance of the hull at the towing test
	S		distances sailed
	S_i	5.4	signals
	t	2.2	thrust deduction fraction
	t_H	2.4	thrust deduction parameter
	t	2.2	time
	tau	3.8	relative velocity increase
	T	2.2	thrust of the propeller
	T_0	2.6	thrust parameter
	T_p	4.8	predicted thrust of the propeller
	T_E	2.2	effective thrust of the propeller
	T_H	2.6	thrust parameter
V	V	2.2	speed of the hull relative to the water
V	V_0	4.7	speed of the hull over ground
	V_p	4.8	predicted speed of the hull relative to the water
V_A	V_A	3.4	speed of the propeller

			at the open water test
	V_D	4.7	speed of the water relative to the ground, drift
j	V_E	3.8	energy speed of the propeller
	V_P	3.3	speed of the propeller
	V_{PQ}	3.4	speed of the propeller according to torque identity
	V_{PT}	3.4	speed of the propeller according to thrust identity
w	w	3.3	total wake fraction
	w_D	3.8	displacement wake fraction
	w_E	3.8	energy wake fraction
	X_N	4.5	partial derivatives with respect to frequency of revolutions
	X_V	4.5	partial derivatives with respect to speed

9. Tables

9.1 METEOR and Model Data

	METEOR	Model	Dummy	
length between perp's	90.000	6.204	3.977	m
length submerged	93.862	6.416	4.184	m
breadth in water line	16.500	1.138	1.138	m
depth at FP	4.776	0.329	0.334	m
depth at AP	4.976	0.343	0.343	m
displacement with app's	4463	1.464		m^3
surface with app's	1172	8.428		m^2
propeller diameter	3.000	0.207		m

Further details : see table 9.2

9.2 METEOR and Propeller Data

9.3 Traditional Model Tests

9.4 Traditional Model Results

9.5 Rational METEOR Results

9.6 Rational Model Results

9.7 Rational Dummy Results

10. Figures

10.1 List

1 Propulsion data and efficiencies

2 Model of the ship system

3 Shafting arrangements

4 Measuring set-up on the shaft

5 Wiring on the shaft

6 Calibration of the shaft

7 Calibration of the shaft

8 Detail of the calibration

9 Calibration of deformations

10 Calibration of temperature

11 Installation in the tunnel

12 Installation in the tunnel

13 Detail of the shaft

14 Computer system configuration

15 Terminals in the drawing room

16 A test condition

17 Another test condition

18 Flow behind the propeller

19 Route in the Greenland Sea

20 Average service conditions : Froude numbers

21 Average service conditions : thrust ratios

22 Average service conditions : torque ratios

23 Test 040 : frequencies of revolution raw

24 Test 040 : thrust raw

25 Test 040 : torque raw

26 Test 040 : distances sailed raw

27 Afterbody of the model

28 Forebody of the model

29 Dummy forebody of the model

30 Results of model tests

31 Thrust and torque ratios

32 Loss parabolas, wake fractions

33 Propeller efficiencies

34 Thrust deduction fractions

35 Hull efficiencies

36 Total efficiencies