Evaluating Ship Speed Trials: Identifying Parameters of Powering Models

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Despite serious discomfort of industry with the traditional procedure of evaluating ship speed trials a Japanese proposal, refining past practice, has become draft standard ISO/DIS 15016. In the interest of the profession an in-depth discussion of the fundamentals and an alternative standard has been suggested and is being promoted.

Based on surprisingly simple ideas, originally developed as a by-product of the METEOR project, the author has developed a consistent systems identification method with a minimum number of explicit acceptable models and requiring no reference to model test results and other prior data, *as it should be*.

Parameters of propeller performance in the behind condition and of current velocity are simultaneously identified by solving one set of linear equations. Subsequently parameters of the shaft powers required due to water, wind and wave resistance are simultaneously identified by solving a second set of linear equations.

The ISO/DIS 15016 example and the EVEREST data constructed by Tamura provide comprehensive test cases. Differences remaining in the results of traditional and rational evaluations can be ascribed to inconsistencies in the ISO procedure and in the inverse procedure of constructing test data.

The typical samples of six, at best eight or ten 'doubtful' averages from 'steady' runs are of course too small for 'serious' applications of statistical methods. In the METEOR and CORSAIR trials quasisteady test manoeuvres have been performed and shown to provide not only more, but more reliable information, at the same time references necessary for the suppression of systematic errors due to the feed back of noise, even at service conditions in heavy weather.

This paper, commemorating the 2nd INTERACTION BERLIN '91, the Second International Workshop on the Rational Theory of ShipHull-Propeller Interaction and its Applications at VWS, the Berlin Model Basin, June 13-14, 1991, is another example of problems solved by the rational theory of propulsion. In view of the applications the fundamental problem is being treated as a stand-alone problem. The results will be convincing as such, but hopefully generate interest in other aspects of the general theory as well.

1 Traditional approach: partial models

It is a great privilege and honor being invited for the fourth time to present a piece of my work aiming at a rational theory of ship propulsion here at St. Petersburg, where Leonhard Euler has published among other works on hydrodynamics his Scientia Navalis in 1749, two volumes of a general theory of rest and motion of floating bodies, and where he found his own rest at the St. Lazarus cemetery in 1783.

The evaluation of the powering performance of ships based on speed trials is one of the basic problems of ship theory. Maybe due to the difficulty of this problem and its lack of color it is not fashionable with chairs of ship theory, practitioners being left alone with the intricate fundamentals and the difficult details. In view of the requirements of ISO 900x and of the legal aspects and implications this situation is felt to be unacceptable. Continued work in the spirit of Euler towards a decent theory of trials meeting acceptable 'standards' and criteria is necessary.

Traditionally the performance evaluation of ships, newly built in particular, is based on trials consisting, in view of the costs, of only a minimum of steady double runs up and down wind, waves and current, the double runs being required to provide for the necessary variability of the data. If at a given time steady conditions are reached the speed over ground, the shaft rate of revolutions and torque as well as the relative wind speed and the sea state are being measured or estimated, respectively.

The evaluation of these data according to established procedures is based on a large number of conventions: models of hull propeller interaction, of losses in the shafting and of wind and wave resistance according to the state of the art in ship theory requiring values of many parameters to be estimated on the basis of prior information: results of model tests for the particular ship, systematic wind tunnel tests, seakeeping theories and other data.

The results of the evaluations do not only depend on the observations of the environmental conditions, particularly the more or less crude measurements or estimates of the wind and wave data, but on the many partial models adopted and the values of their parameters estimated, and last but not least, due to the ill-conditioned problems to be solved, on the ill-defined numerical methods applied as well.

2 Sensitivity: need for standardization

This sensitivity is not a problem of the traditional method alone, but an inherent property of the problem to be solved. And this sensitivity is exactly what urgently requires adequate standardization in order to arrive at comparable, 'objective' results. The author does not share the opinion expressed by English colleagues in the discussion of ISO/CD 15016 that the procedure cannot be standardized.

The sensitivity is particularly unsatisfactory in view of the decisions, the settlement of contractual disputes, to be based on these results. The need for standardization resulted in a number of well known codes of practice and recommendations. The latest move has been the Japanese Committee Draft of an ISO standard, which in the meantime has become the Draft Standard ISO/DIS 15016.

The conventional character of the very involved traditional procedure proposed is completely covered up by 'physical' details. Instead of addressing the fundamental problems a Japanese/Korean battle on seakeeping theories is being fought, without noticing that the basic problems at hand cannot be solved by more advanced hydromechanical theories. In any case the estimation of added resistance du to waves is based on very crude estimates of the sea state, the wave height and the wave period.

Any attempt to settle all the problems mentioned by increasing the complexity of the traditional practice and standardizing it, is doomed to fail. With practitioners such attempts are widely felt to be not only unsatisfactory, but to be inadequate, not addressing any of the fundamental problems mentioned, including systematic errors in the measurement of the relative wind speeds and in the estimation of the sea states. Even if the latter will be replaced by measurement of the seaspectra the problems will not be solved.

Consequently the author is promoting the necessary clarification and rationalization As a first reaction to the Japanese ISO/CD an alternative proposal of an adequate standard has been drafted. The reservations were and are, even stronger now, that an ISO standard should not just continue to refine past practice, but should meet the highest 'standards' and take advantage of the latest state of the art and technology in every respect.

3 Rational approach: overall models

The proposal drafted has been based on the theory of rational conflict resolution, which calls for utmost transparency. In order to settle a conflict rationally basic concepts and propositions as well as rules of definition and deduction have to be agreed upon, in other terms: an axiomatic system has to be adopted. In view of the application under trials conditions this system should be as simple as possible, the few concepts necessary preferably directly measurable or observable and the few propositions preferably as plausible and 'self-evident' as possible. After such a transparent system has been adopted the logical consequences derived according to the accepted rules of deduction will be acceptable for the parties involved.

The starting point is, not as usual the momentum balance, but the energy balance at steady conditions

$$d_t E = P_{S.sup} - P_{S.req} = 0 \, ,$$

using simple 'local' overall models of the shaft power supplied by the propeller and of the shaft powers required by the resistance due to water, wind and waves, and using the technique of parameter identification.

The necessarily conventional procedure can be 'rationalized' if: the traditional 'partial' models are aggregated to the bare minimum number of 'overall' models with the bare minimum of parameters solely to be identified on the basis of the measurements taken, advanced systems identification methods are being applied consistently.

In the proposal developed and the numerical demonstrations provided during the discussions on the ISO/DIS 15016 it has been shown that such a procedure is not only possible, but provides more consistent results than the standard method proposed in the draft standard. This paper contains the final state of the development and the results of the final comparison of results.

The parameters identified ad hoc are measures of correlation between the observed shaft power and the observed 'causes'. In case of the supplied power the 'causes' are the frequency of shaft revolutions and the relative speed of the ship through the water. In case of the power required the 'causes' are the relative speed through the water, through the wind and through the waves.

In his discussion of the Report of the ITTC Specialist Committee on Trials and Monitoring to the 22nd ITTC at Seoul and Shanghai September 05/11, 1999, the author has fully endorsed Recommendation 5 to the Conference concerning the recording of 'time histories'. Even if runs are considered stationary sound performance and confidence analyses have to be based on 'instantaneous' values of the data. The present samples of at best eight or ten 'doubtful' averages are just too small in size for 'serious' applications of statistical methods.

As will be discussed in more detail later the very large inertia of ships even extremely small accelerations and decelerations, maybe as small as 5 millionth of a 'g', can completely upset the momentum and energy balances. Establishing steady conditions and taking mean values are two different goals resulting in different values and are not a matter to be left to practitioners. The problem is exactly the same at model tests.

4 Need for cooperation, state of the art

The rational method proposed, being still in its infancy, does not yet cope with all the problems and details. It will need the joint effort and agreement of all experts before it can be established as a reference and as a standard. The advantages of the rational procedure are a minimum number of transparent conventions and the consistent application of simple systems identification methods requiring no reference to model test results and other prior data, *as it should be.*

In the interest of the profession, science and technology, and the customers, yards and owners, a serious discussion not only of the details, but of the fundamentals in the first place, is strongly suggested. Naval architects need to take the discomfort of the industry they are serving very serious and come up themselves with adequate solutions before industry or even outsiders tell them what they better should do or should do better.

Although the ideas, originally developed as a by-product of the METEOR project some ten years ago, are surprisingly simple and the results of the re-evaluation of data are essentially in agreement with the traditional results, the procedure is not readily accepted by naval architects worldwide. But in discussions following presentations of the rational procedure outsiders have already raised the question: 'What else have naval architects done so far?'

On the website of the author a summary of the early development of the rational procedure provides access to numerous examples as does the section 'On the Evaluation of Trials' under What's new? and under Recent Papers. The work has been continued along this line of thought since, the essential result being the axiomatic or conventional theory explained in many papers and presentations, the latest state of development to be discussed in this paper. According to the insights gained during the development and the application of the method an update of the draft alternative standard has been prepared, though still in a rather sketchy way, and may serve as the starting point of a future, adequate standard.

5 Shaft power supplied, current velocity

The propeller performance in the behind condition, in the full scale wake, and the current velocity can be identified simultaneously by solving one set of linear equations.

For screw propellers the shaft power

$$P_P = 2\,\pi\, n\, Q_P$$

can be derived from measured values of the rate of revolutions and of the torque. In case the latter are averages of periodically or stochastically oscillating values already this simple formula is a convention. Further conventions are necessary, if instead of the power in the shaft the power at the propeller is being considered as is the case in the traditional method based on model propeller open water characteristics.

Further the speed of the ship over ground, with reference to an earth fixed observation space, can be measured using the global positioning system GPS, which is readily available today, now even without the previously limited resolution. But the speed of the ship's hull through the water cannot be measured directly due to the unknown current velocity.

This problem can be resolved, if the data observed in a series of steady runs on opposite courses at given times are described by the power law

$$P_P = p_0\, n^3 + p_1\, n^2\, v_H$$

and the hull speed

$$v_H = v_G + v_C$$

expressed as the sum of the speed over ground and the current velocity, and by a model for the current velocity as function of time, maybe harmonic with the tides or just polynomial

$$v_C = \Sigma\, c_i\, t^i\,, \quad i = 0, \dots 3$$

preferably linear in the unknown parameters. Both laws are 'local' in the sense that they apply only in the 'vicinity' of the operational conditions met and can be extrapolated only with great care.

The parameters of the power supplied and of the current velocity can be identified from a sufficient number of independent states by solving the resulting set of linear equations. In view of the ill-conditioned problems arising there is no chance to solve the equations with do-it-yourself algorithms, singular value decomposition is an absolute requirement. The traditional procedures of iteratively solving six, eight or even ten simultaneous ill-conditioned 'noisy' equations remain altogether obscure, to say it politely. They are definitely inadequate.

After this 'calibration' the propeller power characteristic or law in the behind condition can be used to establish the deviation from the contracted conditions and for monitoring purposes. To determine the value of current velocity from measured values of the rate of revolution and of the torque. The speed of the ship through the water is obtained according to the explicit rule

$$v_H = P_P / (p_1\, n^2) + p_0\, n / p_1\,.$$

If the thrust has been measured together with the power, as has ben done on the METEOR and the CORSAIR, the parameters of the thrust law

$$T = t_0\, n^2 + t_1\, n\, v_H$$

can be identified as well. This law after additional calibrations or even crude assumptions can be used to determine the prevailing value of the resistance at a given time, even for ships in ice covered waters.

6 Visualisation, scrutiny: normalization

After the identification of the parameters it is convenient to normalize the results for visualization, discussion and scrutiny. The advantage of the normalized data, the power ratio

$$K_P = 2\,\pi\,K_Q = P / (\rho\, D^5\, n^3)$$

and the thrust ratio

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

is that the power function and thrust functions of two variables reduce to functions of only one variable, the hull advance ratio

$$J_H = v_H / (D\, n)\ .$$

The first two figures at the end of the paper show a comparison of the results according to the rational method and the results according to the procedure proposed in the ISO draft standard. The first figure, the currents versus time shows for scrutiny not only the results including all ten runs, but also the results of the ten possible sub-sets including only nine runs. This scrutiny revealed a misprint in one of the power data. After appropriate correction, still to be confirmed, the subsequent figures show only the results including all ten runs.

Already at this stage it is evident that, according to the principles set forth, the method proposed in the ISO/DIS must be inherently inconsistent. Else the power ratios would not display the very unlikely behavior and deviate systematically from the optimum estimate of the power law. The reason is that the traditional procedures provides a systematically wrong estimate of the current velocity.

Further, the plot of the power ratios versus the hull advance ratios suggests that already at this stage contracted values, typically derived from model tests, can be plotted as well and deviations from the powering law identified can be discussed without the determination of the power required due to resistance and reduced to the no wind and no wave condition. This suggestion has been made by the author in the first proposal of an alternative standard. But the author realized that this was not acceptable in general. Not only the propeller performance, but the ship performance at given conditions, usually the speed-power curve at no wind and waves, is being contracted.

7 Power required due to resistance

So further the powers required due to the resistance in water, in wind and in waves have been identified simultaneously by solving another set of linear equations. Identifying parameters of models from observed data, even visually observed wave data, has the advantage that systematic errors in the observations are 'to a great extent' automatically accounted for by identifying the appropriate correlation factors instead of relying on apriori physical data not accounting for systematic errors in the observations. In case of the proposed, very involved ISO method this is not the case, although it is based on the same wind measurements and the same crude wave observations available. This fact is one major reason for the concerns about the ISO method expressed unisonously by experts in ship yards and model basins.

The shaft power required is due to the motions of the vessel through water, waves and wind. As in the case of the power supplied the parameters of simple 'local' overall models, including the propulsive efficiency, can be identified and used to determine the speed-power relationship at conditions different from the trials conditions, typically at the no wave and no wind condition.

The power due to motion through the water is 'locally', 'in the vicinity' of the operating conditions, sufficiently modeled by the cubic parabola

$$P^{\,water} = \Sigma\, c^{\,water}{}_i\, v_H{}^i,\quad i = 1, 2, 3\ .$$

The power due to motion through the wind is as usual sufficiently modeled by the law

$$P^{\,wind.x} = c^{\,wind.x}\, v^{\,wind.x}\, |v^{\,wind}|\, v_H$$

with the relative wind speed, if the wind direction is basically from ahead or behind. In general the additional law

$$P^{\,wind.y} = c^{\,wind.y}\, |v^{\,wind.y}|\, |v^{\,wind}|\, v_H$$

needs to be introduced to account for the 'directional' coefficient of wind resistance. The indices x and y are denoting the longitudinal and lateral components of the wind speed, respectively.

Slightly more involved is the added resistance due to the operation in waves. The simple law

$$P^{\,wave} = c^{\,wave}\, (h^{\,wave})^2\, v^{\,wave.x}\, |v^{\,wave}|\, v_H$$

with the observed wave height and the relative wave speed derived from the observed wave period, similar to the law of the shaft power due to wind, is being suggested and has been used in the re-evaluation of the ISO/DIS example. An additional law for the transverse waves may be necessary. As in the case of the supplied power and of the current the models proposed are open for discussion and for improvement. They are the conventions to be agreed upon!

The third and the fourth figure at the end of the paper show a comparison of the results according to the rational method and the results according to the procedure proposed in the ISO draft standard, the latter based on the crudely guessed value 0.6 of the propulsive efficiency. Evidently the results are very similar in trend, the quantitative differences are quite remarkable.

8 Singularities proper

If the wind and wave conditions are so closely correlated that the problem finally becomes singular the separation of wind and wave resistance can only be achieved by an additional convention. In this case evaluations are based solely on the relative wind or wave velocity and the overall power factors obtained are reduced the wind and wave power factors

$$c^{\text{wind}} = c^{\text{wind.solely}} / (1 + r^{\text{wave / wind}})$$

$$c^{\text{wave}} = c^{\text{wave.solely}} / (1 + r^{\text{wind / wave}})$$

with the Rayleigh ratio

$$r^{\text{wave / wind}} = \Sigma\, x^{\text{wave}}\, x^{\text{wind}} / \Sigma\, x^{\text{wind}}\, x^{\text{wind}}$$

of the 'wave variable'

$$x^{\text{wave}} = (h^{\text{wave}})^2\, v^{\text{wave.x}}\, |v^{\text{wave}}|\, v_H$$

with respect to the 'wind variable'

$$x^{\text{wind}} = v^{\text{wind.x}}\, |v^{\text{wind}}|\, v_H$$

and vice versa. In the limiting case of perfect singularity the values of both power factors are the same.

This technique has been successfully applied in a case of data provided by a German yard. The results will be available on the website of the author as soon as the permit for publication has been received.

9 Contracted and other conditions

After the parameters of the local laws of required shaft powers have been identified from the trials data the speed-power relationships can be established for the contract conditions, usually the no waves and no wind condition:

$$P_{P0} = P_P^{\text{water}} + P_P^{\text{air}} = \Sigma\, c^{\text{water}}_i\, v_H^{\,i} + c^{\text{wind.x}}\, v_H^{\,3}\ .$$

For the given hull speed and propeller power the frequency of revolution is obtained as the solution of the power equation

$$P_{P0} = p_0\, n^3 + p_1\, n^2\, v_H\ .$$

The power and the rate of revolution as functions of speed through the water are usually compared with the contracted values derived from predictions based on model tests. Using the parameters identified speed-power and speed-revolution relationships at conditions other than the contracted can be derived as well in the same simple fashion within the range of validity of the parameters.

For visualization, discussion and scrutiny the power and the revolutions are again normalized. The normalized data, the power number

$$C_{P0} = P_{P0} / (\rho\, D^2\, V^3)$$

and the advance ratio

$$J_{H0} = v_{H0} / (D\, n)$$

as functions of the Froude length number

$$F_n = v_H / (g\, L)^{1/2}\ ,$$

are much more sensitive and meaningful than the physical data.

The last two figures at the end of the paper show a comparison of the results according to the rational method and the results according to the procedure proposed in the ISO draft standard. Again the differences due to the inconsistency of the traditional method are quite remarkable. The power number according the rational method exhibits extrema due to bow and stern wave interaction as expected.

Surprising, from another point of view, is the fact that despite the inconsistencies of the traditional method the results are nearly correct. This fact could give rise for arguments in support of the traditional method and in support of traditional research into the reasons. From the viewpoint of the author these would be basically wrong arguments and the latter an irresponsible waste of resources.

In case of the CORSAIR tests performed on shallow water the power number showed a sharp peak at a critical Froude depth number as expected.

10 Verification and validation

It is common practice to verify, to prove the correctness of an analysis procedure with test data generated by the corresponding inverse synthesis procedure. Such tests with 'simulated' data are the minimum required in view of programming mistakes and the noise to be dealt with. This technique of verification has been used in Tamura's 'Appraisal of Correction Methods ...' to show the 'superiority' of the Taniguchi-Tamura method. But very clearly the simulated EVEREST data, are not useful to prove the adequacy of the 'basic' procedure nor any alternative procedure, even provided they had been generated correctly and according to the rules set forth.

The numerical results of evaluations with alternative procedures differ 'by definition' from the results according to the 'basic' method. In the case of the EVEREST data extremely careful scrutiny, at first using the rational procedure, later only the data provided, revealed systematic inconsistencies in the test data, maybe produced by the traditional framework underlying their generation and cancelled by the corresponding method of evaluation. Only 'real' data can serve the purpose of validation!

Accordingly, in order to show the adequacy of the rational method proposed the author has evaluated all sets of real data he get hold of, all the examples to be found on his website, in any case including the data and the detailed program of evaluation, according to the state of development at the time of evaluation. But to the knowledge of the author so far nobody cared to look at these examples. Instead, each new party comes up with new data, incomplete as these always are and with their own evaluation, asking to reproduce their results. The problem is that the other methods are hardly ever published in sufficient detail, so usually they cannot even be scrutinized. The yards have of course a massive interest that the situation will remain that way forever!

So computing new examples will never resolve the 'problem' of the author, to convince the community, that the rational method has the advantages of being more adequate, more transparent and providing not only more, but more consistent results. In order to evaluate methods 'strictly' one would have to analyze them formally, not numerically. This would be a very nice students exercise, but a terrible waste of effort in the light of the simple principles set forth. The intensive studies, documented in a series of evaluations of the ISO/DIS example, show, that the problems in detail remain difficult enough. And most of them need to be addressed and solved, even if the evaluation is following the traditional procedure. In the proposed standard the problems have not even been addressed. Although they have been pointed out explicitly by participating bodies, they have simply been ignored.

In order to reach his goal the author urges his colleagues to forget about the data and try to understand the essence of the difficult problem to be solved and try to understand the very simple clear-cut solution proposed including its capability to deal with the few data at hand, not only crude as the wave data are, but maybe even systematically 'wrong' as the wind data. Not the small numerical differences in the results are of interest, but the big differences in the models and, even more so, in the principles! The procedure proposed comprises consistent systems identification methods with a minimum number of simple explicit and acceptable models, requiring no reference to model test results and to any other prior information, as it should be! Not 'acceptable' numerical differences between results of various methods, but acceptable conventions have to be agreed upon!

11 ISO/DIS 15016: example

Despite fundamental deficiencies and inconsistencies, even in the example provided, trials being interrupted by a passing typhoon, the new ISO/CD 15016 example provided a well documented comprehensive test case for the rational procedure proposed and developed in the course of the discussion of the recent activities to standardize the evaluation of ship speed trials. Complete data and evaluation are to found on the website of the author. The plots of the results at the end of the paper show comparisons of results of evaluations according to the rational procedure described in the present paper and according to the traditional procedure described in the draft standard.

The figures show that there remain differences in the evaluations. Independent of further analysis the differences in magnitude and, particularly, in trend of the normalized results between the proposed rational and the proposed ISO evaluations can be ascribed to inconsistencies in the ISO procedure. Some effects may reflect laminarity effects at slow speed model tests results used in the ISO method.

A problem arises in analyzing the required power. At extreme weather conditions the residua are not small as in case of the supplied power. The reason for this phenomenon is doubtless the poor resolution of the wave observation. If the crude model is kept the residua have to be accounted for. From the data at hand the values of the added power due to waves being identified according to the rational method are about as large as the 'nominal' values computed according to the proposed ISO method. The latter has been particularly conceived to deal with this problem, just with reference to the very crude data of wave observation, but without any reference to the observed data of shaft power!

In order to avoid any discussion on purposely selecting data, the data of all ten runs have been included in the evaluation. This has the advantage to increase the size of the sample for statistical evaluations. In addition to the evaluation of all ten runs evaluations have been performed of the ten possible sub-sets of data of only nine runs. The stability of the results is very good, showing the nearly perfect consistency of the original data with only one exception as mentioned. After much deliberation and scrutiny the exception has been ascribed to a misprint in the power data of the third run. In the evaluation the value 11**5**49 kW has been used instead of 11**3**49 kW as printed in the draft standard. The question has not yet been resolved, the data are being checked down to the roots.

12 Quasi-steady states: inertial effects

Noting that often the time constant of the propulsor is much smaller than that of the vessel, the requirement of steady states, which are difficult to establish and to guarantee, can be relaxed and the full energy balance

$$P_P = P_R + dE / dt$$

with the basic definition

$$d_t E = c^{inert} v_G dv_G / dt$$

can be used, if the changes of kinetic energy are properly monitored and accounted for. In view of the relatively small longitudinal hydrodynamic inertia and the small range of interest this is another acceptable convention.

In general the additional parameter may be identified together with the other parameters of the required power. The acceleration may be determined directly from the GPS measurements. Due to ship motions in a seaway, even the small pitching motions of a model in a model basin, it is impossible to determine the extremely small values of interest by means of gravity field meters, alias accelerometers.

The rate of change of the kinetic energy is the power required due to the inertial resistance. Due to the large masses of ships extremely small accelerations may upset the energy balance, if they are not appropriately accounted for! Practitioners are well aware of this effect and 'take advantage' of it, if possible, if the contractor does not notice. In case the longitudinal inertia of the ship, including the hydrodynamic inertia, can be estimated reliably on the basis of other data this method provides a check of the propulsive efficiency and the thrust deduction.

Many problems in the evaluation of trials are due to waiting for steady conditions, i. e. ignoring a great deal of useful information, and using ill-defined average values. In the METEOR and CORSAIR trials quasisteady test manoeuvres have been shown to be much superior to steady testing, providing not only much more information, but at the same time the necessary references for the suppression of systematic errors due to feed-back of noise of noise, even at service conditions in heavy weather.

The method proposed for the evaluation of ship speed trials may take quite some time to make its way into practice, although the technology is available. But in view of modern optimum ship design it is more than timely that the present, unsatisfactory practice is supplemented and, maybe some day, replaced by the more transparent, more rational and 'more physical', still conventional procedure. The models used are the crudest possible constitutive conventions, but they may serve the purpose until somebody comes up with more adequate proposals.

The procedure of parameter identification may be generalized to identify effects of load conditions. Up to now data available for the identification are simply being ignored! The ISO/DIS does not even address this problem usually solved by referring to model test results at various load conditions.

13 Further detailed analysis

As has been shown further in the METEOR and CORSAIR trials the additional measurement of the thrust permits a complete analysis of the hull-propeller interaction, based on the axiomatic theory proposed by the author. It can be envisaged that in future the method will be applied for the evaluation of model tests and trials and for monitoring of ship performance in service, and thus eventually increasing and improving the data base on scale effects. In the METEOR project the evaluation included thrust deduction as well as displacement and energy wake fractions, permitting for the first time ever the direct determination of scale effects, even in the thrust deduction fraction. Validation of CFD codes introduced into ship design can be successfully achieved only along this route.

The simple thrust deduction axiom introduced has been shown to be efficient and plausible. While the determination of the thrust deduction fraction requires additional performance data observed during quasisteady propulsion tests the wake fraction, the jet efficiency and the hydraulic efficiency of the propeller can be determined from traditional steady trial tests. The lost power axiom has been shown to be equally plausible. But the determination of the wake ratio is more involved and more sensitive. This sensitivity is not a property of the rational method but due to the nature of the problem. After much deliberation all attempts to find a simpler and more robust method, preferably avoiding extrapolations to the states of vanishing advance ratio and vanishing thrust, are felt to be doomed to fail.

14 Reasons for inconsistencies

In the present context the rational theory of ship hull-propeller interaction is of interest as it permits to show explicitly some of the inconsistencies of the traditional method of performance analysis. The axiomatic theory is abstracted from the theory of ideal propulsors in uniform displacement and energy wakes, serving as a sufficiently complex model. Although this is implied by the traditional teaching and in all engineering considerations, it has never before been done explicitly and coherently.

In this theory the thrust deduction fraction as a function of two parameters, the ratio of displacement and energy wake fractions and the jet or ideal efficiency of the propulsor, used as a measure of propeller loading. This shows that all former attempts to establish a relation between wake and thrust deduction fractions were doomed to fail. The essential parameter, the wake ratio, is not even identifiable in traditional ship model testing. So historical data cannot be re-evaluated!

Further, the values of the wake ratio are different on model and on full scale. At the condition of equal load ratio the values of the thrust deduction fraction are consequently different on model and on full scale, contrary to the traditional axiom of model ship correlation, which postulates equal values on model and on full scale. This and other inconsistencies of the traditional evaluation of ship performance have triggered the work of the author on propulsion showing that a consistent rational procedure is not only possible, but practical. In the meantime the complete thrust deduction relation has been used for scaling purposes at other places as well.

In case of traditional single screw configurations the question may be raised: Why should the traditional method of evaluation be replaced as long as it provides the ‘right’ answers, despite its internal inconsistencies? In cases of non-traditional configurations the method proposed adapted to the particular problems is the only ‘alternative’, the only possible method. In the SES CORSAIR project, where the traditional methods of performance analysis fails due to the lack of adequate open water tests with the semi-submerged propellers, it has been shown that even the inertia of the ship and the resistance in shallow water can be identified reliably.

15 Propellers conceived as pumps

In principle all considerations so far are based on the concept of the propeller as a pump, which can be treated in terms of volume flow and energy density or in terms of mass flow and mass specific energy. This aspect is also of fundamental importance for the design and the evaluation of propulsors other than screw propellers. While usually in pumps the thrust is a nasty by-product, in propulsors it is of primary concern. In pump design the thrust is treated implicitly and this can be done in propulsor design as well, permitting to account implicitly for complex hull propeller interactions. In ordinary propeller design for thrust the thrust deduction fractions have to be known in advance. This is possible with the data basis available. But it is impossible in case of advanced hull integrated propulsor designs due to larger number of parameters and the lack of a sufficient data base.

As in the evaluation of trials the forgoing considerations support the departure from the naive concept of propellers as thrusters overcoming the resistance of the bodies to be propelled. Much more adequate is to conceive propulsors as pumps feeding energy into volume flows preferably the energy wakes. The condition of self-propulsion is the condition of vanishing net momentum flows into the hull-propulsor systems. All pumps producing the same jet 'far behind', are equivalent! As has been shown this concept is extremely powerful for propulsors in uniform wakes and in 'real' non-uniform wakes. The underlying model *permitting the solution without explicit reference to hull-propulsor interactions* is the model of the equivalent propulsor in the energy wake alone, in plausible terms: the equivalent propeller 'far behind the ship', if there were no diffusive decay of the wake.

This model is not a physically realizable propeller, but an extremely powerful conceptual tool, which has been used already by Horn in Germany for the study of hull-propeller interactions, but its potential has never been fully realized and exploited. In Russia the same model is being used, surprisingly with different results. The paper on design and evaluation of ducted propellers presented at the Centennial of the Krylov Ship Research Institute was intended to continue the discussion and hopefully clarify some of the issues. Among other goals the present paper wants to remind that this question is still open. In the spirit of Euler we have to continue clarifying basic notions, among them such 'simple' problems as the evaluation of trials. According to the experience of the author the 'simple' problems are usually the most fundamental and the least understood.

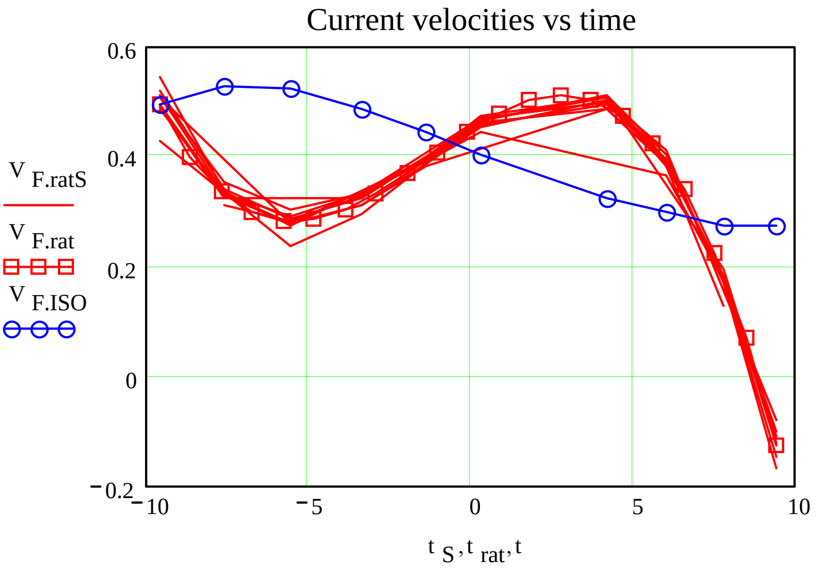
References

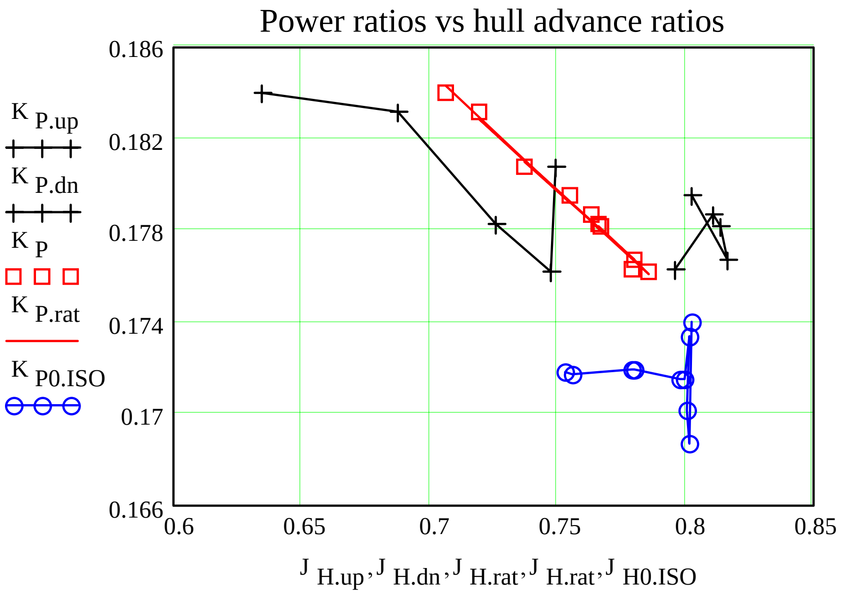
All related studies, including the details of all examples investigated, and all presentations so far are to be found on the website http://www.t-online.de/home/m.schm of the author under What's new? and Recent Papers in the sections 'On the Evaluation of Ship Speed Trials', 'On the Propulsion Tests with METEOR', 'On the Propulsion Tests with CORSAIR'**.** Further, background information is to be found in the Bibliographies related to General and Propulsion.

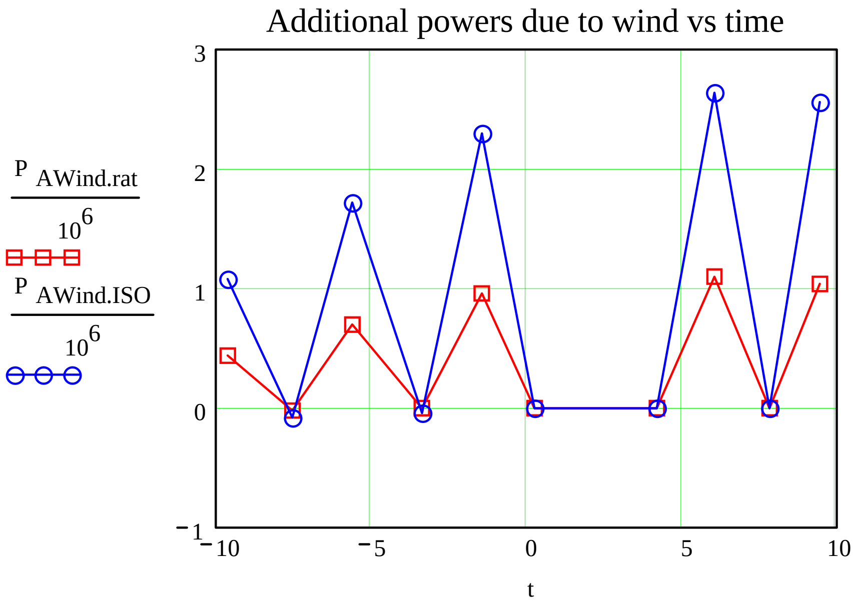
For ready discussion and reference the present paper including hyperlinks *to related material and the* presentation *of the paper are to be found on the website as well.*

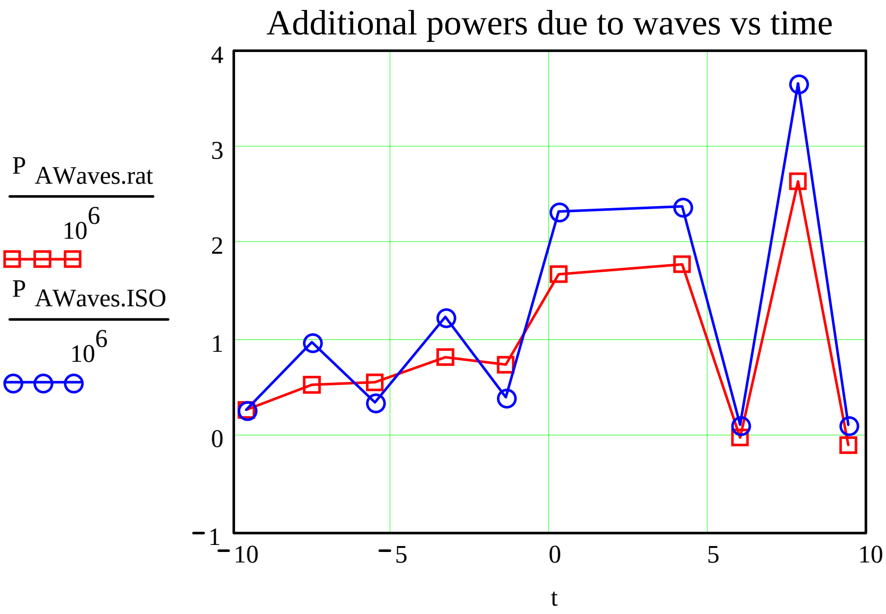
Table of figures

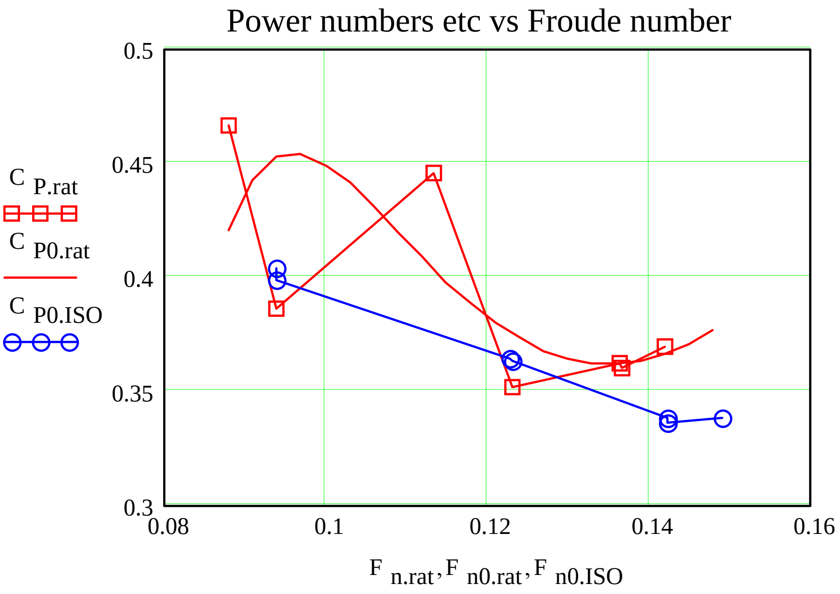
Figure	**Ordinate**	**Abscissa**
1	Current velocities [m / sec]	Time [h]
2	Power ratios	Hull advance ratio
3	Powers due to wind [MW]	Time [h]
4	Powers due to waves [MW]	Time [h]
5	Power factors at no wind and no waves	Froude number
6	Hull advance ratios at no wind and no waves	Froude number

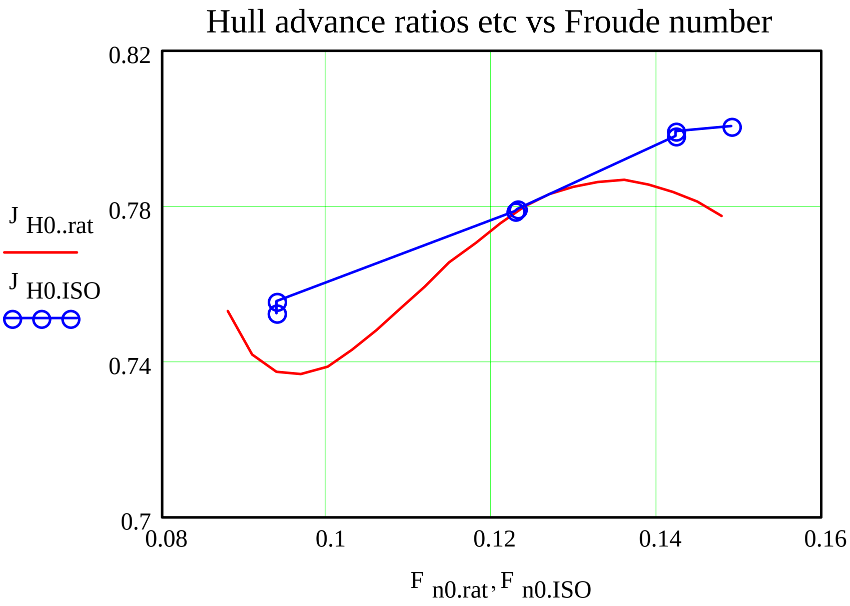

Current velocities vs time
0.6
0.4
0.2
0
−0.2
−10
−5
0
5
10
V F.ratS
V F.rat
V F.ISO
t S, t rat, t


Power ratios vs hull advance ratios
0.186
0.182
0.178
0.174
0.17
0.166
0.6
0.65
0.7
0.75
0.8
0.85
K P.up
K P.dn
K P
K P.rat
K P0.ISO
J H.up, J H.dn, J H.rat, J H.rat, J H0.ISO


Additional powers due to wind vs time
3
2
1
0
−1
−10
−5
0
5
10
P AWind.rat / 10^6
P AWind.ISO / 10^6
t


Additional powers due to waves vs time
$\frac{P_{AWaves.rat}}{10^6}$
$\frac{P_{AWaves.ISO}}{10^6}$
4
3
2
1
0
−1
−10
−5
0
5
10
t


Power numbers etc vs Froude number
$C_{P.rat}$
$C_{P0.rat}$
$C_{P0.ISO}$
0.5
0.45
0.4
0.35
0.3
0.08
0.1
0.12
0.14
0.16
$F_{n.rat}, F_{n0.rat}, F_{n0.ISO}$


Hull advance ratios etc vs Froude number
$J_{H0..rat}$
$J_{H0.ISO}$
0.82
0.78
0.74
0.7
0.08
0.1
0.12
0.14
0.16
$F_{n0.rat}, F_{n0.ISO}$