Propulsor Hydrodynamics

by Michael Schmiechen, Berlin[1]

Abstract

Based on results of earlier systematic tests with a ducted propeller a rational theory of propulsion has been conceived since 1968, explicitly since 1980 in terms of an axiomatic theory of hull-propeller interactions, and has been developed over the past twenty five years until now. As neither propeller design nor powering prediction belonged to the duties of the author at VWS, the Berlin Model Basin, the whole development took place beside the 'mainstream', thus permitting to shed light on that stream and its future developments.

Keywords

rational theory of propulsion, evaluation of steady trials, hull-propeller interactions, evaluation of quasi-steady trials, METEOR: full-scale tests and scale effects, propulsors as pumps, design not(!) for thrust

Experience

It is a great honour and privilege to be invited for this theme lecture on Propulsor Hydrodynamics. The session will cover a wide variety of propulsors and many of their aspects in detail. The purpose of this talk, as I understand it, is to provide some guide lines and perspectives, which will protect us from getting lost under way.

The perspectives are clearly the personal views of the author on the future developments based on forty years of experience at VWS, the Berlin Model Basin. Since 1903 until the end of the war VWS has been the German navy tank, being completely destroyed during the war, and later rebuilt as an institute, reporting to the city of Berlin, doing navy work only secretly, as secret as possible under Russian eyes. After the unification of Germany VWS became part of the Technical University of Berlin and has finally been closed down at the end of the year 2001.

The author has gained further experience in the international community, the ITTC in particular, six years as secretary of the Executive Committee (Schmiechen, M. (Editor): Proc. 13th ITTC Berlin/Hamburg, 1972) and fifteen years on the Symbols and Terminology Group (Schmiechen, M. (Editor): ITTC Symbols and Terminology List, Version 1993. San Francisco 1993).

Clearly experience and tradition are not very interesting *per se*, especially if somebody or even whole generations do the wrong things for decades. So do not belief anybody, not even me, but stick to the slogan of rationalism: *sapere aude*, dare to think yourself.

My first tasks at VWS have been systematic tests with a ducted propeller, 1961, as well as theoretical investigations of unconventional propulsors. These tasks forced me to reconstruct the basic theory of propulsion from first principles. My results on hull-duct interaction contradicted the deeply rooted beliefs of my director and my supervisor so much that the report was not registered as a VWS Report proper and

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vanished in the basement. Although dismantled as plain superstition the professional 'principles' of my director and my supervisor are still around.

Based on this experience my rational theory of propulsion has been conceived years later, since 1968, explicitly since 1980, and developed over the last twenty five years until now. As neither propeller design nor powering prediction belonged to my duties at the model basin *the whole development took place beside the mainstream, thus permitting to shed light on that stream and its future developments (Feyerabend)*.

A consequence of the traditional practice is a lot of confusion. Ernst Mach, 1896: "... als Forschungs-Mittel ist jede Vorstellung zulässig, es ist aber nothwendig, von Zeit zu Zeit die Darstellung der Forschungs-Ergebnisse von den überflüssigen unwesentlichen Zuthaten zu reinigen ..." ('… as a *means* of research any conception is acceptable, but it is necessary from time to time to clean the *results* of resarch from unnecessary additions …'). Mach was not the first, to point out the necessity of intellectual hygiene, but the influence of his work on all heroes of modern science has been over-whelming.

Ship theory/Systems theory

There will be hardly any time to go into the details of the underlying philosophy although it has played and continues to play a dominant role in the work of the author. Only so much: Propulsor hydrodynamics is embedded into ship theory and, even more basic, hydromechanical systems theory, a subset of classical mechanics. And: The concepts of ship theory have clearly to be distinguished from their interpretations in terms of results of hydrodynamical experiments, physical and/or numerical.

If we do not understand the purpose and working principle of a propulsor, how can we possibly talk about propulsor hydrodynamics? Similarly we have to have an adequate concept of resistance of real ships, with propellers and in wind and waves, and a practical way to provide its operational interpretation. This is the lesson naval architects can learn from Einstein.

The motto of this lecture is taken from Paul Feyerabend, 1965: 'Immediate plausibility and the agreement with the usual jargon indicate - far from being philosophical virtues - that not much progress has been achieved or will be achieved.'

Buckingham's Π -Theorem

We are solving our problems by more or less involved models. Before talking about special models I will mention some general conditions these models must meet. In order to be useful for the description of objective relationships the models must be invariant with respect to changes of units. Buckingham's Pi-Theorem is the expression of this meta-principle (Birkhoff, G.: Hydrodynamics. A study in logic, fact and similitude. New York: Dover, 1955; pages 77-90). Colloquially it is referred to as dimensional analysis; figure 1, slide 12.

An important, often forgotten observation is that the theorem says nothing about the number and type of parameters to be chosen and the format of the function. This information is a matter of *experience*, past or present, not necessarily of hydrodynamics. The parameters can be changed to others, amounting to a change to oblique coordinates in logarithmic scales. Although everybody learns this at school, hardly anybody draws the conclusions.

The reduction in the number of parameters by three appears to be large, but the number of mostly geometrical parameters, necessary to describe a hydromechanical system, is usually very large. As a consequence aggregate or global parameters, typically 'characteristic' lengths are of interest, usually a matter of more, mostly less educated guess work trying to anticipate the results of the tests to be performed.

Example: Speed trials

Often the situation is even simpler and the problem at hand can be solved pragmatically. Let us consider as a simple, but most fundamental example, the powering performance of a ship at given loading condition and speed; figure 2: slide 15, figure 3: slide 16, figure 4: slide 17.

And Buckingham's theorem says nothing about the values of the parameters. This is a matter of experiments. The few parameters of the model can be identified from the few data usually obtained during traditional steady speed trials. The slide shows the results of the evaluation of the data provided with the example in the recently internationally agreed standard ISO 15016: 2002-6; figure 5: slide 19.

Only after the acceptance of ISO 15016: 2002-06 ship theoreticians and model basins appear to realise that they have for incredibly long time completely neglected the most fundamental problem of ship theory, the evaluation of the performance of ships under service conditions. Besides a paper on the 'Evalution of the Service Performance of Ships' by Poul Andersen, Anne Sophie-Borrod and Hervé Blanchot (Marine Technology 42 (2005) 4, 177-183), evidently driven by Kappel's 'enthusiasm', MARIN at Wageningen has started a new JIP (Joint Industry Project) 'to bring sea trials up to speed' (Report, Sept. 2005, no. 86, 16).

ISO 15016: 2002-06

The important observation is that contrary to the poor results of the standardised practice of our grandfathers based on hydrodynamic considerations the rational evaluation of speed trials provides perfect results without any reference to hydrodynamics. I only mention that the same methodology can be used to determine the performance at no wind and no waves.

The analysis can be greatly improved if it is not based on obscure averages, but on the quasi-instantaneous values preferably of quasi-steady tests, providing for variability and not suppressing all relevant information as is done in traditional steady speed tests.

The international agreement has been reached although the foregoing results have been communicated *in time* to all organisations and bodies involved. Only the Korean colleagues have opposed the new standard, but for the wrong reason. They wanted to introduce more hydrodynamics, an even more fancy seakeeping theory 'based' on shaky grounds, the crude estimates of the sea state. The failure of the traditional method confirms a basic rule in hydromechanical experiments: *If the flow velocity has not been estimated correctly you can safely forget everything else;* figure 6: slide 23.

This very simple, but fundamental example clearly shows that the present, very involved practice is largely based on superfluous assumptions, to put it mildly. But who likes to be told that his deeply rooted beliefs are plain superstition? So far I have not met anybody, including myself! But some colleagues started to use the procedure proposed. The last data I had a chance to evaluate are those of trials from a ship with adjustable pitch propeller tested in the Marmara Sea.

Trial codes

During the period of the 23rd ITTC apart of the Propulsion Committee three Specialist Committees have been dealing with matters of propulsion: Speed and Powering Trials, Procedures for Resistance, Propulsion and Open Water Tests, Validation of Waterjet Test Procedures.

The report of the Specialist Committee on Speed and Powering Trials provides a comparison of all trials codes currently in use. The method proposed has been considered as "a category by itself. It does not really follow the same format as all the other methods and hence was not used in the comparison of factors reviewed in each method." *Purposely it does not follow the same format!* According to my experience and to the ISO example the problem is not so much to analyse random errors, but the dominant problem is still to avoid conceptual and systematic errors.

To my big surprise the Specialist Committee on Speed and Powering Trials has been discontinued. Evidently the governing bodies of ITTC 'felt' that all problems have been solved, at the same moment member organisations and other bodies concerned finally started to be concerned. On the other hand a Specialist Committee on Powering Performance Prediction has been established, charged with the task which traditionally has been the essential task of the Propulsion Committee and *to which I will turn shortly.*

Inspectional analysis

Not all problems are as simple as the evaluation of speed trials. A rational procedure to arrive professionally, without guess work at formats and parameters of the unit-free function is to adopt axiomatically some simple, though adequate, sufficiently rich hydromechanical model and to perform an 'inspectional' analysis (Birkhoff).

The important observation is that the theory is essentially a normative theory, models unfolding representation spaces, the parameters being the 'coordinates' of the systems considered. When I tell hydrodynamicists that their only task is to identify the values of the parameters defined by ship theory, their reaction is usually quite emotional. This reaction does not change the situation, but supports my argument.

Identification of parameters

Identification is essentially a matter of experiments, either physical or computational, and their evaluation as in the foregoing example. The important point is that these sub-tasks can be performed professionally, preferably *not* by hydrodynamicists.

To put it bluntly: *There are too many hydrodynamicists in towing tanks!* In view of this fact the ITTC had a hard time finally to come back to its original task, to agree on standard procedures. As a major achievement the Quality Systems Group has established a quality manual in accordance with ISO 900x under its chairman Strasser, SVA Vienna.

In line with the reorientation of ITTC the Propulsion Committee of the 24th ITTC 2005 was charged among others with the task to "… Monitor and follow the development of new experimental techniques and extrapolation methods. … Review the ITTC Recommended Procedures, benchmark data and test cases for validation and uncertainty analysis and update as required. Identify the requirements for new procedures, benchmark data, validation and uncertainty analysis and stimulate the research necessary for their preparation."

My point is that the uncertainty analysis is cura *posterior.* In future much more work has to be done along the conceptual lines I am sketching today.

Hull-propeller interaction

Again I shall provide an example of fundamental importance to our profession, further analysis of the powering performance, of hull-propeller interactions in particular, required for the powering performance predictions. Without going into the details I shall scan through the theory in order to provide some background for the discussion of the results in particular and in general.

Required is a more detailed model and the acquisition of additional data, namely thrust data, necessary for the identification of the additional parameters. The most convenient way to generate an adequate model is *the axiomatic use the hydrodynamic theory of ideal propulsors in ideal displacement and energy wakes*. Up to now this has been done implicitly, rather vaguely. *My suggestion is to do it explicitly.*

This model provides for conventions, which are implicit or coherent definitions of the hull resistance of a ship with propeller and the propeller advance speed in the behind condition. Again hydrodynamicists are up-set by this crude, mechanical engineering use of their sacred science. But this is the only rational way to solve the problems at hand: to replace hull towing tests and propeller open water tests. *These tests, if* *performed in case of advanced hull propeller configurations, provide useless data and, most importantly, they cannot be performed on full scale under service conditions.*

Momentum balance etc

The first basic equation is the momentum balance: figure 7: slide 36. In view of the limited variability of the data often the quadratic *local* resistance law with only three parameters may be adopted. If the tests cover a wider range there is no problem to generalise this 'law' appropriately.

The thrust deduction fraction is a function of the relative velocity increase, the vorticity parameter, a function of the jet efficiency, the inverse measure of the propeller loading, the first fundamental and convenient parameter, and a second fundamental parameter the displacement influence ratio, different at model and ship due to scale effects; figure 8: slide 37.

Evidently there is no way to arrive at the function by 'induction' based on results of experiments. Of interest is the global approximation leading to the plausible thrust deduction axiom, a relationship between thrust deduction fraction and jet efficiency; figure 9: slide 38. Even this simpler function is unknown, due to the fact that the displacement influence ration does not occure in the traditional analysis of naval architects.

The four parameters introduced are obtained as solution of a system of linear equations *provided the jet efficiency has been determined before*. And this problem can be solved as follows.

Energy balance etc

The second basic equation is the energy balance for the propeller with the 'ideal' or jet efficiency and the 'hydraulic' or pump efficiency; figure 10: slide 39. Usually naval architects do not separate these efficiencies, although only the pump efficiency permits to judge the quality of the propulsor.

The jet efficiency is a function of the apparent propeller load ratio and the apparent propeller efficiency, both obtained from measured magnitudes. Solving for the wake ratio results in a first function for the wake; figure 11: slide 40.

From the 'plausible' wake axioms and the further axiom concerning the pump efficiency in the range of interest the second function is obtained; figure 12: slide 41.

Equating the two functions results in a non-linear equation for the parameters to be solved iteratively. After the solution has been reached all powering performance parameters may be determined in the range of observed hull advance ratios.

A 'model' test

Results of a quasi-steady model test, figures 13 to 18: slides 43 to 48, obtained accordingly have been compared with results of a corresponding traditional steady tests, evaluations based on hull towing and propeller open water tests; figures 19 to 26: slides 49 to 57.

Thus the coherent model and the coherent set of data obtained from a quasisteady model test of only two minutes duration permit to identify coherent results in a wide range of propeller advance ratios. This technique is the only meaningful in case of wake adapted propellers, pre- and post-swirl configurations, partially submerged propellers etc. The paper of Kooiker et al is concerned with the importance of coherent measurements in the context of cavitation and pressure fluctuations.

At low propeller loading the losses at additional surfaces of pre- and post-swirl systems out-balance the gains. Thus only 'contra'-sterns and -rudders requiring no extra surfaces offer 'real' advantages. Before the war already thirty percent of the tonnage was fitted with 'twisted' sterns and rudders. Since the war each generation of naval architects has re-invented the idea, but I have not heard of routine applications. A perfect engineering solution is the new Becker rudder.

History and future

Horn's early attempts in 1935/37 to solve the problem of wake for such configurations suffered from conceptual limitations and deficiencies of the measuring and computing techniques in those days. They were finally disrupted by the war and started anew with my axiomatic theory in 1980. From there on it took me twenty-five years of hard work to reach the present state of maturity.

Anybody, not totally blind on both eyes, will see the technological and commercial advantages of the procedure. For example extended experimental studies necessary for the validation of computer codes can thus be performed *very quickly, very cheaply and, last but not least, most reliably over wide ranges of parameters*. Necessary changes of the geometrical parameters pose 'the only real' problem in this context.

Scale effects

The Propulsion Report at the 23rd ITTC deals with the well known scale effects in model screw propeller performance essentially without drawing consequences. The usual 'way out' is to perform open water tests, even with wake adapted propellers, at 'sufficiently' high Reynolds numbers. But in model propulsion tests the propellers are usually run at much lower Reynolds numbers, though in the behind condition. And the powering performance analysis is based on these two sets of incoherent data!

Consequently my opinion is that model test should not be performed at slow speeds, where we are picking up scale effects unnecessarily aggravating the problem of partial similarity. Accordingly I have evaluated the METOR model data only at the model speed.correspoding to the service speed.

At the 23rd ITTC Holtrop reported on quasi-steady testing at MARIN. In the 'hybrid' model adopted the inertial term is missing. So the question arises: Is the inertia being treated statistically, assumed to vanish in the average? Some forty years ago, in a Japanese study it has been shown, that even very small accelerations, less than a thousand of a 'g', may easily upset the momentum balance.

And I have observed that taking averages or, even worse, relying on ill-defined averages provided by somebody else may be 'exactly' the wrong thing to do. Traditional methods usually rely on *steady conditions, not averages,* and thus the steady conditions may have to be 'established' or constructed as I did in the METEOR project!

Full scale tests

As has been mentioned the method can be applied on full scale. Results of full scale tests with the German research vessel METEOR in November 1988 in the Arctic Sea, figure 27: slide 67, have been compared with results of corresponding model tests providing scale effects in wake and thrust deduction fractions, *for the first time worldwide,* figure 28: slide 68. These scale effects are the corner stones of reliable powering performance predictions.

Quasi-steady tests have also been performed on model and full scale with the experimental air-cushion vehicle CORSAIR/MEKAT of B+V fitted with partially submerged propellers. As described in the paper by Shibu the latter for various reasons are of great interest to navies. Accordingly there is little published information available.

The present and future work and publications of Suresh and Suryanarayana promise to change that situation, although their systematic series is limited to the open water performance. Figures 29, 30: slides 71, 72 show performance of the propellers behind the CORSAIR model tested in the large circulation tunnel UT2 of VWS. Figures 31, 32: slides 73, 75 show results of full scale quasi-steady propulsion tests just before the 'hump'.

The paper by Rath et al is discussing the design of super-cavitating propellers or trans-cavitating as they are now being called. But from the abstract it is not quite clear whether the authors are really designing super-cavitating or partially submerged propellers as well.

Power prediction

Going back to first principles fundamental problems of ship theory so far unsolved have been solved. Although everybody is talking about the need for full scale tests, the ITTC has discontinued the Specialist Committee on Trials and Monitoring! The institute that first will introduce the techniques described will certainly be at the forefront of the scientific and professional development. Not only navies can use the technique for monitoring purposes etc.

The paper of Go et al is concerned with the problem of model testing and power prediction for large ships with a CRP-POD system. In case of podded drives Froude's test technique using hull towing and propeller open water test appears to be adequate. If the method of model testing described before is developed for application not only on model scale, but on full scale as well, the scale effects of interest can be determined directly. In the Report of the 24th ITTC Propulsion Committee Go's procedure has been discussed in some detail.

In that Report mention is being made of the Committees dealing with the problems of podded drives: "Model testing and full-scale performance prediction for podded propulsors and waterjets are difficult in itself, and test procedures and prediction methods are currently being studied by the current 24th ITTC Specialist Committees on Azimuthing Podded Propulsion and on Validation of Waterjet Test Procedures, respectively. The testing and full-scale performance predictions are even more complex and difficult for hybrid propulsors."

In view of the latter "the Committee recommends that a new test procedure and fullscale performance prediction method be developed for this hybrid concept." The essential point of the rational procedures is to get away from the ever more detailed models generating more problems than solving them and to move towards highly aggregate models with only few parameters to be identified from the few data available. This permits to evaluate trials without reference to model test results and other prior information, *as it should be*. Unless we start evaluating trials as objectively as possible we cannot reasonably talk about scaling.

Propulsors as pumps

The solutions so far have been based on the naive conception of a propulsor as thruster overcoming the resistance of the hull to be propelled. In advanced hull-propulsor configurations, maybe pump jets, 'starting' with ducted propellers, this point of view is no longer adequate. *Thrust is no longer a meaningful measure of performance and no longer a meaningful goal of design. Consequently the concept is to be ‘deleted from our intellectual inventory’.*

In the Report of the Propulsion Committee of the 24th ITTC 2005 on page 75 we still read: "Estimating wake and thrust deduction and understanding the influence of scale effect is also being improved by more realistic information on the flow field in and around the hull-waterjet system, …"

An alternative much more adequate and efficient conception is to consider propulsors as pumps feeding energy into the fluid and establishing the conditions of self-propulsion, vanishing net momentum flow into the hull-propulsor systems. The simplest of such pumps are ducted propellers.

The ideal ducted propeller provides a much more 'realistic' model of a propulsor than the actuator disc, as it does not sufferi from edge singularity. The sketch, figure 33: slide 82, clearly shows that the purpose of ducts is *not* to provide thrust, *but* to avoid edge singularities and thus approach ideal propeller performance. Most expositions of the theory of duct are quite inadequate and misleading. And the higher the thrust of the duct the higher the frictional losses at the duct and the danger of cavitation at the actuator.

Most design methods are still concerned with ducted propellers in open water. And the methods to deal with hull-propeller interactions are very crude, to say it politely. In view of the fact that interactions mostly take place between hull and duct this approach is neither realistic nor acceptable. Suction at the hull and thrust at the duct constitute an energetically neutral hydrodynamical short circuit, figure 34: slide 85, a fact that has long been known to pump builders.

Adequate language

Pre-requisite for an efficient description and treatment of the problems at hand are adequate languages, concepts and propositions. The basic concepts are: speed of ship, power supplied, density of fluid, volume flow rate, energy flows at the entry and at the exit. Any reference to the naïve conception of propulsion, the concept of thrust in particular, is carefully avoided.

For equivalent propulsors, *being formal constructs*, *not real propulsors*, outside the displacement wakes ‘far behind, in the energy wake alone’ the magnitudes are the same; figure 35: slide 86. The concept of equivalent propulsors has been introduced by Fresenius and first systematically exploited by Horn at Berlin.

Among the derived concepts the energy velocities are the most prominent, figure 36: slides 87. The axioms comprise the energy and the momentum balance, and in addition the axiomatic definition of the effective thrust; figure 37: slide 88. The performance criteria, the internal efficiency and the configuration efficiency, figure 38: slide 89, in terms of energy are particularly important in view of comparison of various configurations as discussed in the paper by Karimi. Usually decisions are based on inadequate performance criteria and non-equivalent propulsors. A historical example is Grim's vane wheel.

A more recent example is the thorough investisgation of the Kappel propeller, even fullscale (Marine Technology 42 (2005) 3, 144-158). The very careful comparison with an optimum standard design remains unsatisfactory as long as the configuration efficiencies and the pump efficiencies of the propellers have not been 'measured'.

A resulting theorem concerns the powering performance, figure 39: slide 91, depending on three parameters, the 'internal' hydraulic efficiency, the energy wake fraction and the vorticity parameter, figure 40: slide 92. The vorticity parameter, another fundamental parameter not 'normally' used by naval architects, clearly shows that only the effective resistance and thus the effective thrust is energetically relevant.

The Committee on Unconventional Propulsors under its chairman Kruppa, TUB Berlin, was fully aware of the advantages of 'talking' in terms of energy flows. But the following committee decided to go back to the description in terms of momentum flows. As the author has pointed out in a contribution to the discussion at the ITTC in Venice 2002 both descriptions have to complement each other if it comes to forces and design for strength.

Design method

A corresponding method for the design of wake adapted ducted propellers has been proposed and tested. It starts from an invariant design goal, figure 41: slide 96, not requiring a clumsy search for an optimum, but concentrating hydrodynamics to the essentials, design and evaluation and testing of the pump proper. Starting from the condition self-propulsion, of overall zero momentum flow, essentially from the effective resistance and the corresponding net power to be fed into the flow; figures 42, 43: slides 97, 98.

As in pump design everything else is being dealt with in terms of energy flows and the thrust and all interactions are being treated implicitly observing the optimum condition from the beginning! *As in pump design the thrust comes in only at the end, as a nasty by-product.* All pumps develop thrust and need thrust bearings. Although pump designers do not want to produce thrust, they cannot avoid it and have to know it in order to design the bearing.

In the paper by Banerjee et al detailed wake measurements have been made in a wind tunnel at NSTL. With the design procedure mentioned the "*Large-scale(?) search for the optimum vehicle-propulsor configuration for fully submerged vehicles" or its genetic development?* might have been greatly accelerated, if not unnecessary. Usually the constraint on the body contour is too narrow. In a fully integrated design the hull does not need to be tapered, 'stream-lined'!

Cavitation

The cavitation performance of a similar system has been investigated at NSTL in physical and numerical experiments as described in the paper by Kumar et al. The draft abstract raised questions concerning the basic hydrodynamical mechanisms, the flow inside the propulsor and the cavitation in a boundary layer.

The paper of Chatterjee et al is concerned with the problem of ultra sonic cavitation reduction in combination with decelerating ducts. The paper by Suryanarayana et al is concerned with differences in cavitation noise of contra-rotating propellers made of different materials. Acoustic experiments in narrow basins suffer from the very limited useful frequency window.

The pump industry has standards of delivery, so naval architects do not need to re-invent the wheel. 'Integral' testing of complete propulsor systems including the inlet can be performed in by-passes of cavitation tanks as described in the paper of Roussetsky et al. At VWS inlet tests have been performed that way in 1980's. To calibrate flow meters for large flow rates within a confidence interval of 3% is far from trivial; PTB Berlin.

Conclusions

The purpose of this talk was to provide some guide lines and perspectives concerning propulsor hydrodynamics. As I have demonstrated, in talking about propulsors hydrodynamic experiments, physical and/or numerical, come in only after simple hydrodynamical models constituting an adequate normative ship theory, unfolding representation spaces have been adopted. The examples I have shown do not solve *all* problems, but are paradigmatical in character.

Only on this level of abstraction can parameters, performance criteria and development strategies be defined in a professional, efficient fashion. Paul Feyerabend in his famous treatise 'Against Method' of 1975 stated: 'The only general principle, not impeding progress, is: *anything goes*.' Accordingly I took the freedom to choose the engineering principle KISS: *Keep it simple, stupid*. And I hope to have demonstrated how successful that is in protecting us from professional superstition and guess work.

The question is no longer how to 'disprove' my approach and the conceptual framework successfully developed and applied in various fundamental cases in detail, *but to take competitive advantage* of them as power tools for the solution of other problems at hand, e. g. the design and evaluation of research strategies and of test techniques, the construction of adequate performance criteria etc. In view of the technological development in experimental hydrodynamics, e. g. CFD, naval architects can no longer afford to be content the conceptual framework of their grandfathers.*The question is: If the author could do this, what can I do next*?

References

The papers submitted and presented at the present conference have not been available, but only draft abstracts could be referred to.

Recent surveys of the state of the art in propulsor hydrodynamics with detailed references are to be found in the Reports of the Technical Committee on Propulsion and the various Specialist Committees on matters of propulsion in the Proceedings of the 23rd ITTC at Venice in 2002 and of the 24th ITTC at Edinburgh in 2005. These Reports are also to be found on the websites of the ITTC: http://ittc.sname.org/proceedings.htm and http://www.ittc.ncl.ac.uk/reports/papers.htm, respectively, the latter with more than 250 references to recent work.

A complete account of the work done at VWS over one century is to be found in: Schmiechen, M.: Jubiläum der Eröffnung der Versuchsanstalt für Wasserbau und Schiffbau in Berlin am 07.07.1903. Vortragsveranstaltung der Fachausschüsse 'Geschichte des Schiffbaus' und 'Schiffshydrodynamik' auf der Schleuseninsel in Berlin am 22. November, 2003. Vorträge und Verzeichnisse von VWS-Berichten, VWS-Mitteilungen und STG-Beiträgen gesammelt und herausgegeben von Michael Schmiechen. STG Nr. 3010, VWS Mitteilungen Heft 60, post mortem Berlin 2003. In memoriam Versuchsanstalt für Wasserbau und Schiffbau, Berlin.

References to work of the author concerning problems of propulsion are to be found on his website http://www.m-schmiechen.homepage.t-online.de under 'Bibliography: General' and 'Bibliography: Propulsion'. Complete papers of the author and their presentations since about 1990 are to be found under 'Recent papers' and 'What's new?'.

List of symbols: *none*

The body of the paper purposely does not contain symbols. Symbols introduced in the context of the following figures/slides are explicitly defined. A separate list of symbols would duplicate these definitions without the context necessary.

List of figures

Buckingham's theorem …

Theorem. *The assertion that the relation*

$$Q_0 = f(Q_1, Q_2, \ldots\ Q_{n-r} \ldots Q_n)$$

is unit-free is equivalent to a condition of the form

$$\Pi_0 = \phi(\Pi_1, \Pi_2, \ldots\ \Pi_{n-r})$$

for suitable dimensionless power-products Π *of the Q, where*

n denotes the number of influence magnitudes Q, homogeneous in the basic units, and

r denotes the number of independent basic units: in mechanics r = 3.

Example: Speed trials

Often the problem can be solved pragmatically. Let us consider as a simple, but fundamental example the powering performance of a ship at given loading condition and speed.

In this case the power ratio

$$K_P \equiv P / (\rho\, D^5 N^3)$$

is assumed to be a function

$$K_P = f_P(J_H)$$

of the hull advance ratio

$$J_H \equiv V / (D\, N)\ .$$

Practical limitations

Due to the very small variability of the data *the most general function that can be identified with confidence* is a linear function

$$K_P = K_{P0} + K_{PH} J_H\ .$$

With the ship speed over ground, to be measured by GPS, and the unknown current speed over ground the hull advance ratio is

$$J_H = J_G - J_C\ .$$

More pragmatism

Again the problem can be solved pragmatically by introducing formally a polynominal law for the unknown current velocity as function of time

$$V_C = \sum_i v_i \, t^i \, .$$

This completes the model as far as it is of interest here.

The few parameters of the model can be identified from the usually very few data collected at speed trials.

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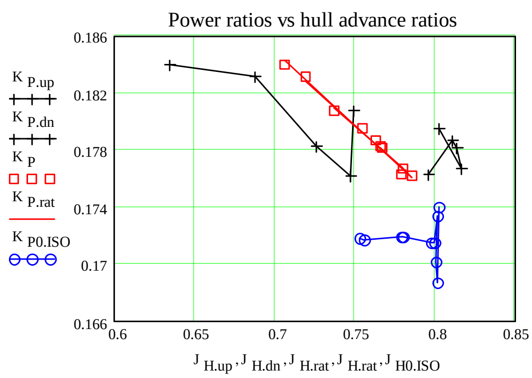
Propeller ‘behind’: ISO example



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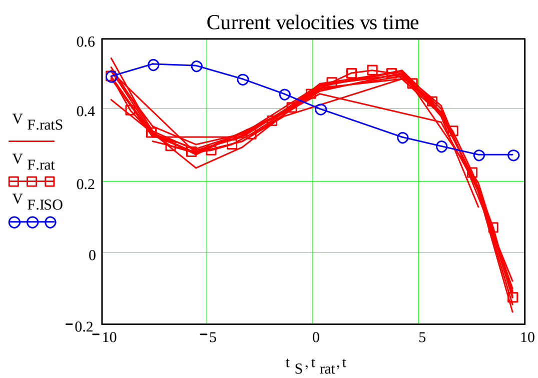
Current: ISO example



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Momentum balance

The first basic equation is the momentum balance

$$m\,a + R(V) = T\,(1 - t)\ .$$

In view of the limited variability of the data often the *local* resistance law

$$R(V) = r_0 + r_1\,V + r_2\,V^2/2$$

with the three parameters r_i may be adopted.
If the tests cover a wider range there is no problem to generalise this 'law' appropriately.

Thrust deduction function

The complete thrust deduction function is

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

with the relative velocity increase as function of the jet efficiency

$$\tau = 2\,(1/\eta_{TJ} - 1)$$

and a parameter not occuring in the traditional analysis, the displacement influence ratio

$$\chi \equiv w_D / (1 - w_E - w_D)\ ,$$

different at model and ship due to scale effects.

Thrust deduction axiom

Of interest is the global approximation

$$t \approx 0.56\,\chi\,\eta_{TJ}$$

leading to the plausible thrust deduction axiom

$$t = t_{TJ}\ \eta_{TJ}$$

with the parameter

$$t_{TJ} = \text{const}\ .$$

The four parameters introduced are obtained as solution of a system of linear equations *provided the jet efficiency has been determined before*. And this problem can be solved as follows.

Energy balance

The second basic equation is the energy balance for the propeller

$$T\,V\,(1 - w) = \eta_{TJ}\,\eta_{JP}\,P_P$$

with the the 'ideal' or jet efficiency

$$\eta\,T_J \equiv P_T / P_J$$

and the 'hydraulic' or pump efficiency

$$\eta_{JP} \equiv P_J / P_P\ .$$

Usually naval architects do not separate these efficiencies, although only the pump efficiency permits to judge the quality of the propulsor.

Wake function

The theoretical function for the jet efficiency is

$$\eta\,(1 - w) / \eta_{JP} = 2 / [1 + (1 + c / (1 - w)^2)^{1/2}]$$

with the apparent propeller load ratio

$$c \equiv 2\,T / (\rho\,V^2\,A)$$

and the apparent propeller efficiency

$$\eta \equiv T\,V / P_P\ ,$$

both obtained from measured magnitudes.
Solving for the wake ratio results in the function

$$w_1(\eta_{JP}) = c\,\eta / (4\,\eta_{JP}) - \eta_{JP} / \eta + 1\ .$$

Wake axioms

The 'plausible' wake axioms are

$$w = w_{TJ}\,\eta_{TJ}$$

with the parameter

$$w_{TJ} = \text{const}\ ,$$

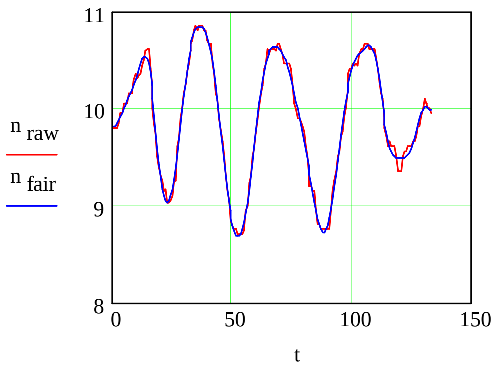
and the further axiom concerning the pump efficiency in the range of interest

$$\eta_{JP} = \text{const}\ .$$

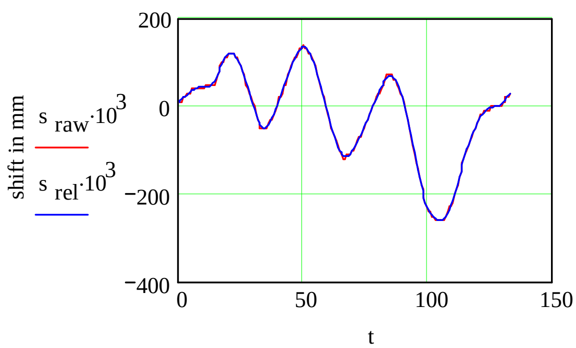
Thus the second explicit condition is

$$w_2(\eta_{JP}, w_{TJ}) = 1 / [1 + \eta_{JP} / (\eta\,w_{TJ})]\ .$$

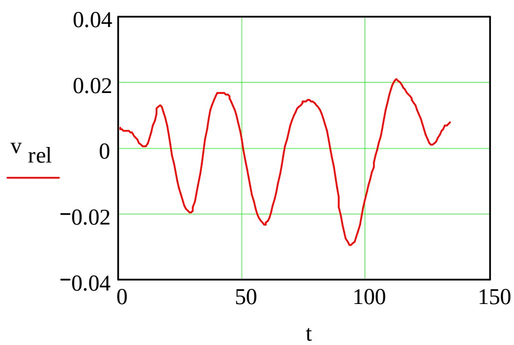
Raw data: rate of revolutions



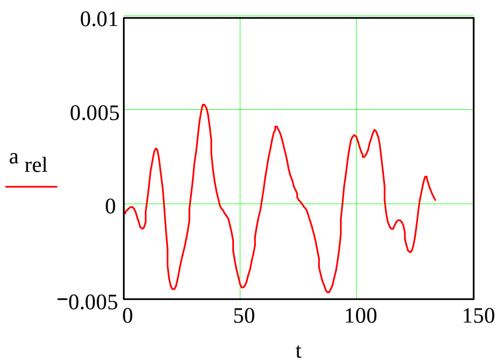
Raw data: relative surge



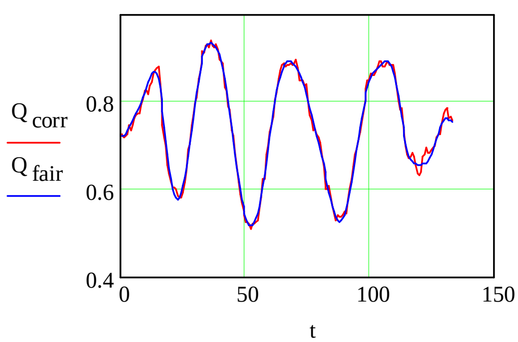
'Derived': relative speed



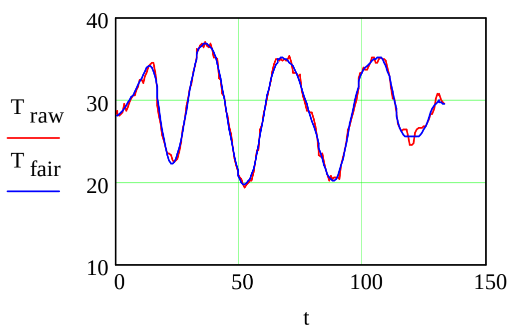
'Derived': acceleration



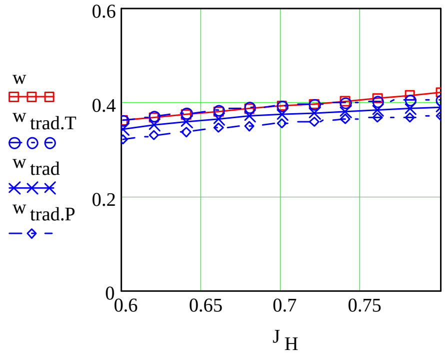
Raw data: torque



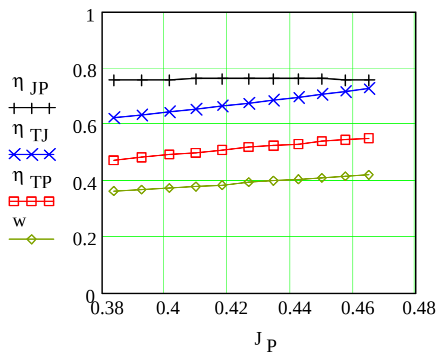
Raw data: thrust



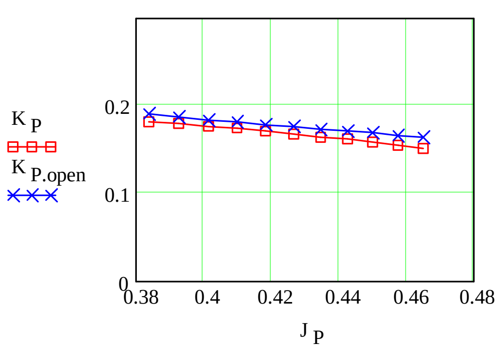
Wake fractions



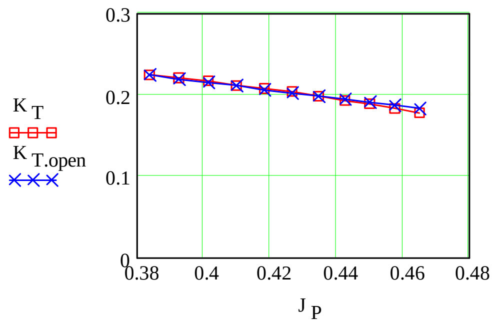
Equivalent open water



Power ratios $K_P = 2\,\pi\,K_Q$



Thrust ratios



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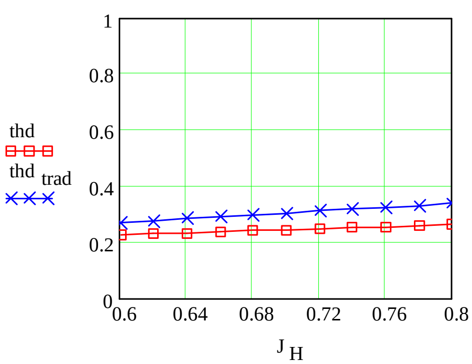
Thrust deduction fractions



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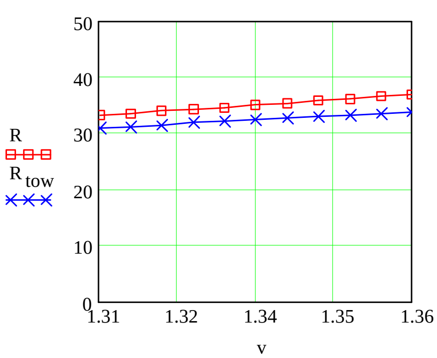
Resistance values



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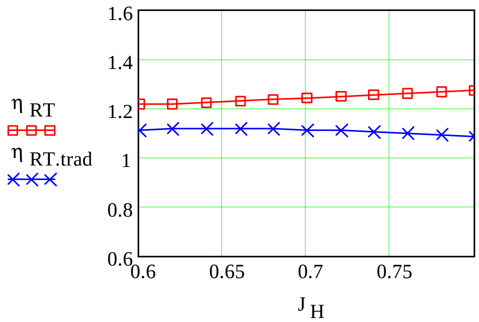
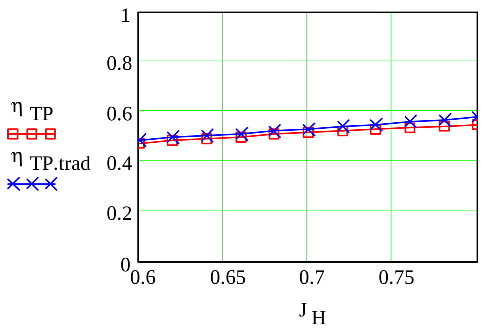
Hull 'efficiencies'

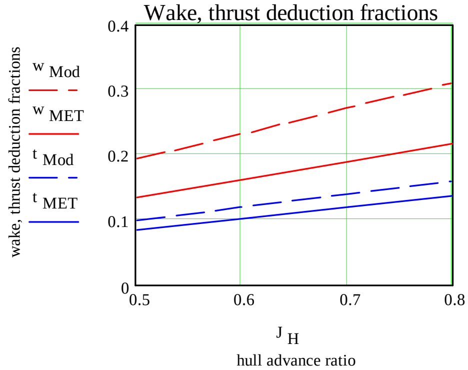


Propeller efficiencies 'behind'

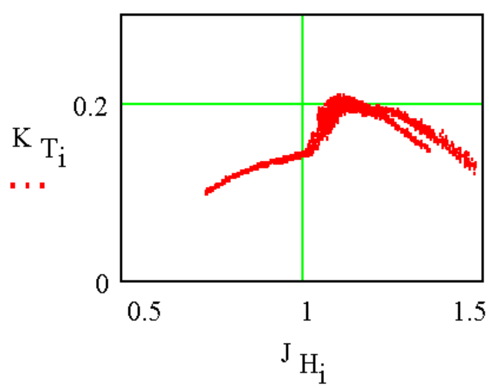


METEOR: Test conditions, *1988*

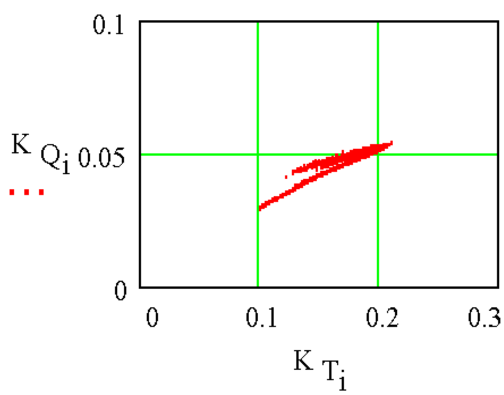
METEOR: Scale effects



Model $K_T = f\ (J_H)$

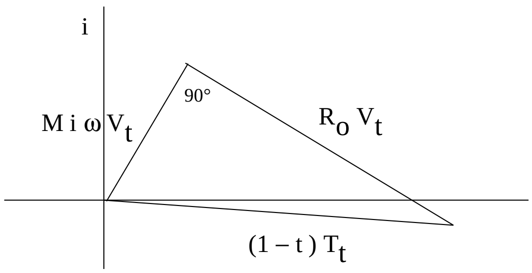


Model $K_Q = f\ (K_T)$



Complex force diagram

First harmonics of covariance functions, constant thrust deduction fraction assumed



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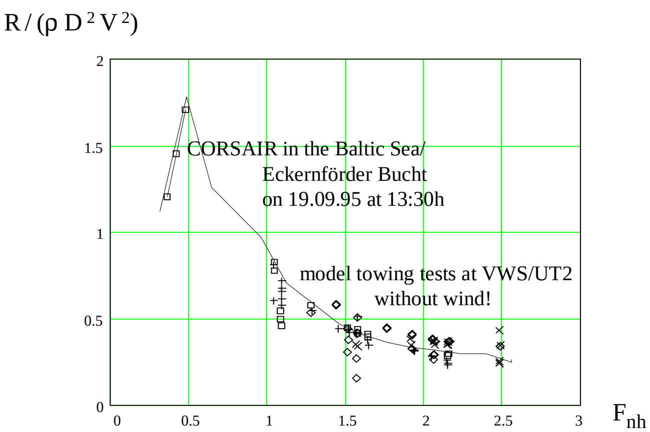
Resistance: shallow water



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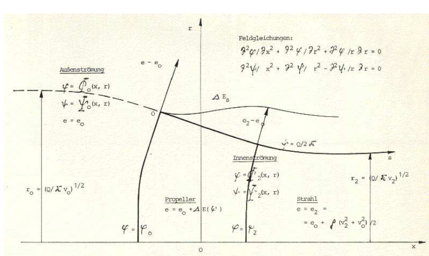
Ideal ducted propeller, *1978*



- outside flow: flow around a sink
  sink 'strength' < propeller flow rate!!!
- actuator: finite potential force field
- boundary stream line (duct): force free!

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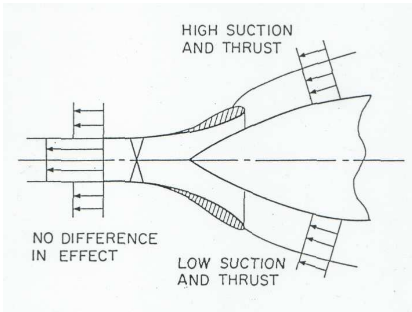
Daniel Bernoulli in action

Suction at the hull and thrust at the duct constitute an energetically neutral hydrodynamical short circuit.
Busmann, STG 1935,
Schmiechen, ONR 1968.



Basic magnitudes

Pre-requisite for an efficient description and treatment of the problems at hand are adequate languages, concepts and propositions.

Speed of ship V_H, power supplied P_P,
density of fluid ρ, volume flow rate Q,
energy flow at entry $E^F{}_E$ / at exit $E^F{}_J$.

For equivalent propulsors, *being formal constructs*, *not real propulsors*, outside the displacement wakes 'far behind, in the energy wake alone' the magnitudes are the same.

Derived: energy velocities etc

Energy velocities	$V_X \equiv (2\,E^F{}_X / (\rho\,Q))^{1/2}$
energy wakes	$w_X \equiv 1 - V_X / V_H$
energy densities	$e_X \equiv E^F{}_X / Q$
actuator head	$\Delta e \equiv e_J - e_E \equiv \Delta\,E^F{}_X \equiv$ $\equiv \rho\,(V_J{}^2 - V_E{}^2) / 2$
'momentum' flows	$M_X \equiv \rho\,Q\,V_X \equiv$ $\equiv (2\,\rho\,Q\,E^F{}_X)^{1/2}$

Axioms

The energy balance with the jet power

$$P_J = E^F{}_J - E^F{}_E = Q\,\Delta e\ .$$

The momentum balance

$$m\,d_t\,V_H + R_E = T_E + F\ ,$$

at steady condition of self-propulsion

$$R_E = T_E$$

with the effective thrust

$$T_E = M_J - M_E = \rho\,Q\,(V_J - V_E)\ .$$

Performance criteria

Independent of the design:

configuration efficiency	$\eta_{TE\,J} \equiv T_E\,V_H / P_J$
internal efficiency	$\eta_{J\,P} \equiv P_J / P_P$
propulsive efficiency	$\eta_{TE\,P} \equiv \eta_{TE\,J}\,\eta_{J\,P}$

Propulsive performance

The configuration efficiency is

$$\eta_{TE\,J} \equiv T_E\,V_H / P_J = V_H / (V_E + \Delta V / 2)\ .$$

Thus the propulsive efficiency

$$\eta_{TE\,P} = \eta_{J\,P} / (1 - w_E + \tau_E / 2)$$

depends on three parameters only :

the *internal efficiency*, the *energy wake fraction*

$$w_E \equiv 1 - V_E / V_H$$

and the vorticity parameter

$$\tau_E \equiv \Delta V / V_H = T_E / (\rho\,Q\,V_H)\ .$$

Vorticity parameter

The vorticity parameter, another fundamental parameter not 'normally' used by naval architects, clearly shows that only the effective thrust, and thus the effective resistance is energetically relevant.

In terms of the normalised propulsor 'head'

$$\Delta\varepsilon = \Delta e / (\rho\, V_H^{\,2} / 2)$$

the vorticity parameter is

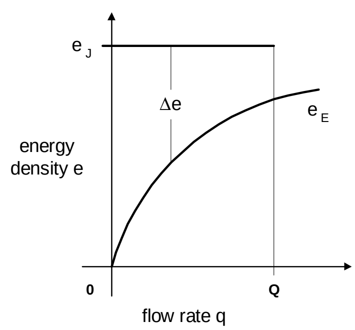
$$\tau = [(1 - w_E)^2 + \Delta\varepsilon)]^{1/2} - (1 - w_E)\ ,$$

and thus in first approximation

$$\tau \approx \Delta\varepsilon / [2\,(1 - w_E)]\ .$$

Design goal

'Invariant' design goal for all optimal, wake adapted ducted propellers including all hull-propeller interactions!



'Pump': stator, rotor, duct

‘Pump’: behind *Amtsberg*'s ‘cigar’