MAHY 2006
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Propulsor Hydrodynamics

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Theme lecture

The session will cover a wide variety of propulsors and their many different 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.

Perspective: *future*

The perspectives are clearly my personal views of the future developments based on forty years of work at VWS, the Berlin Model Basin, documented in great breadth and depth on my website.
But ***this does not imply that I will be telling anecdotes. I shall rather talk about the future: the origin, development and future of ideas, of basic models, underlying 'assumptions'***, usually not explicitly stated in reports and papers, but *of crucial importance for the success and value of the work reported.*

Contra inductive

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**.

When I wanted ***to reconstruct ship theory for my purposes at hand I did not ask naval architects but rather 'architects' of theories.***

Intellectual hygiene

A consequence of the long traditional practice is a lot of confusion and inefficiency. *If space engineers would have had the traditions of naval architects we would not have been on the moon yet.*

Ernst Mach (1896): ***the philosopher as sweeper***:
'... as a ***means of research*** any approach is permitted, but from time to time it is necessary to clean the ***results of research*** from unnecessary, non-essential additions …'.

My motto

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.'**

Do not try to grasp all details of the picture I try to draw, but ***follow the main lines of thought now and only afterwards try to find out the impact on your own work!***

Outline of paper

Some philosophy: *identification*
traditional configurations
traditional trials: *speed/power*
quasisteady trials: *interactions*
explicit theory: *new axioms*
a 'model' test: *of two minutes*
full scale tests: METEOR, CORSAIR
advanced configurations
mechanism: *propulsors as pumps*
design: *thrust as nasty by-product*
some conclusions: *what next?*

First tasks, *1961 …*

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 filed as a VWS Report proper and was banished into the basement.

But ideas and data cannot be locked up!

… shed light

Based on this experience my rational theory of propulsion has been conceived some years later, since 1968, explicitly since 1980, and developed over the last twenty five years until now.

As neither conventional propeller designs nor powering predictions belonged to my duties at the model basin ***the whole development took place beside the main-stream,*** **thus** ***permitting to shed light on that stream and its future developments*** *(Feyerabend)*.

Basic models

If we do not understand the purpose and working principle of propulsors and do not know how to evaluate their performance, how can we talk in a meaningful way about their hydrodynamics?

In the rational theory of propulsion p***ropulsors are conceived as pumps*** and the ***concept of equivalent propulsors,*** one of the great achievements in **ship theory**, due to *Fresenius (1924),* is considered as key powertool, exploited in Berlin by Horn and later by myself.

'Metaphysics'

Propulsor hydrodynamics is embedded into ship theory and, even more basic, hydromechanical systems theory, a subset of classical mechanics.

The concepts of ship theory have to be distinguished cleanly from their interpretations in terms of results of hydrodynamical experiments, physical and/or numerical.

Our basic requirement is that our 'laws' should be 'objective', independent of our choice of units of measurement.

Buckingham's Π-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.

… says 'nothing'

The theorem says nothing about the number and type of parameters to be chosen and the format of the unit-free function. This information is ***a matter of experience*, *past or present*, *not necessarily of hydrodynamics***.

Although everybody learns this at school hardly anybody draws the conclusions.

Example: speed trials

Often the problem 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.
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

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

Limited horizon

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

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

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

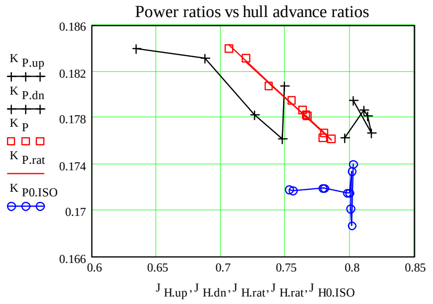
Buckingham's theorem says nothing about the values of the parameters. *They are to be identified from experiments, from the usually very few data collected at speed trials.*

ISO 15016: 2002-06

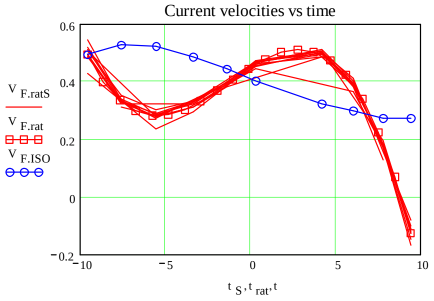
The following two slides show results of evaluations of the data provided with the example of the recently adopted standard ISO 15016: 2002-06.

The international agreement has been reached ***although the following results showing its deficiencies have been communicated in time to all organisations and bodies involved.***

Propeller 'behind': ISO example



Current: ISO example



Grandfathers' practice

Contrary to the poor results of the practice of our grandfathers based on hydrodynamic considerations, ***the rational evaluation of speed trials provides perfect results without any reference to hydrodynamics whatsoever!***

I only mention that the same methodology can be used to determine the performance at no wind and no waves.

'Regula falsi'

In the meantime a working group on naval hydro-dynamics has confirmed that ***the method suggested by ISO 15016 is not only lacking transparency but is error prone***.

Naval architects will have to ask themselves ***soon***: ***How long*** *ship owners, maybe* ***their own Navies, will accept this truly 'incredible' state of affairs?***

Plain superstition

This very simple, but fundamental example clearly shows that ***the present, very involved practice is based on superfluous assumptions***, to put it mildly. But who likes to be told that his ***deeply rooted beliefs are plain superstition?***

The last trials data I had the opportunity to evaluate are those from a ship with *adjustable pitch propeller*.

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 unit-free functions is***

- to adopt axiomatically some simple, adequate, i.e. ***'sufficiently rich'*** *hydromechanical systems model* and
- to perform a dimensional analysis, *an inspectional analysis* (*Birkhoff*).

Emotional reactions

Thus the theory is essentially a normative theory, models unfolding representation spaces, the parameters being the 'coordinates' of the systems considered.

The ***only task*** of hydrodynamicists is ***to identify the values of*** **parameters defined by ship theory**. ***The emotional reactions to this statement do not change the situation, but support my argument.***

Systems identification

Identification is essentially a matter of ***experiments***, either physical or computational, and their ***evaluation***.

These sub-tasks can be performed *professionally*, preferably by ***non***-hydrodynamicists. To put it bluntly: ***There are too many hydrodynamicists in towing tanks!*** *Even the calibration of balances requires experts in systems identification.*

In 'general' an incredibly superficial and careless use of extremely expensive and valuable data is to be observed.

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ITTC Quality manual

In view of this fact the ITTC had a hard time finally to come back to its original task, to agree on standard procedures. It is a major achievement of the present Quality Systems Group, under ist chairman Strasser, SVA Vienna, to have established a quality manual according to ISO 900x.

In future much more work needs to be done along the conceptual lines I am promoting since 1968 and outlining today.

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Hull-propeller interactions

Again I shall provide an example of fundamental importance to our profession, ***further analysis of the powering performance****, of hull-propeller interactions in particular, <u>required for the powering performance predictions</u>.*

Without going into any detail I shall provide only some background for the discussion of the results.

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Axiomatic models

Required are a ***more detailed model*** and the ***acquisition of thrust data***, necessary for the identification of the additional parameters introduced.

An adequate model is ***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* ***the explicit use of this model as model of an axiomatic theory*****.*

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Rational conventions

This procedure 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, 'marine engineering' use of their sacred science.*

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Froude's tests replaced

But this is the only rational way to solve the basic problems at hand*: to replace hull towing tests and propeller open water tests.*

In case of advanced hull propeller configurations the latter tests <u>provide at best useless data</u> <u>and</u>, most importantly, they <u>cannot be performed on full scale under service conditions</u>.

The following slides do not show the complete theory but only ***the axioms replacing hull towing tests and propeller open water tests***.

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Thrust deduction axiom

Starting points are the ***momentum balance*** and the model of the ***equivalent propulsor outside the displacement wake***.

Of interest is the global approximation of the thrust deduction theorem

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

leading to the plausible thrust deduction axiom

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

with the parameter

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

Wake axioms

The starting point is the energy balance …

Correspondingly 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

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

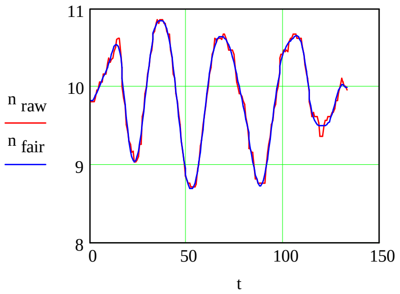
Plausibility checked by open water test results.

Wake: iterative solution

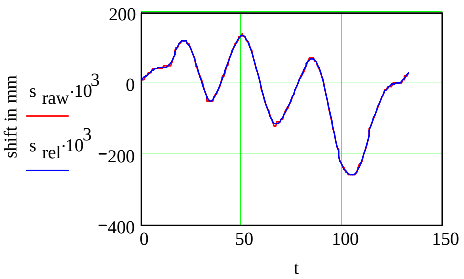
After the solution of the wake problem all powering performance parameters can be determined <u>in the range of observed hull advance ratios</u>.

The following slides show the raw and derived data recorded during a quasisteady 'model' propulsion test.

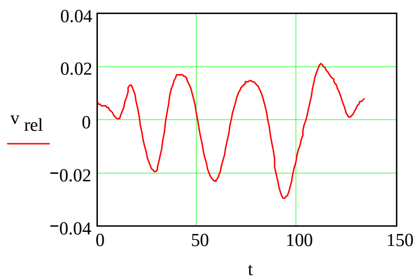
Raw data: rate of revolutions



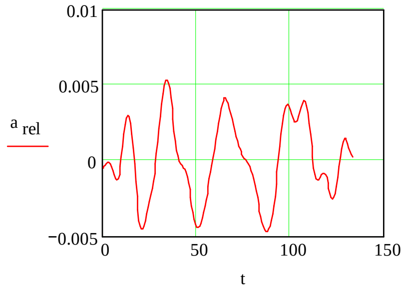
Raw data: relative surge



'Derived': relative speed



'Derived': acceleration



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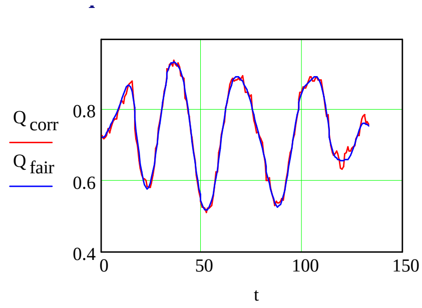
Raw data: torque



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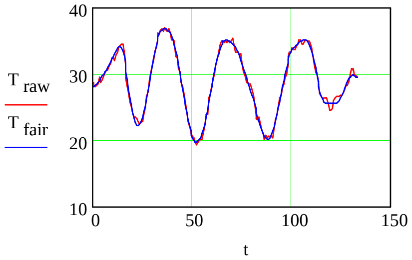
Raw data: thrust



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Results compared

The following slides show only some

- ***results of the rational evaluation*** based on the propulsion tests alone compared with
- ***results of the traditional evaluation*** based on additional hull towing and propeller open water tests.

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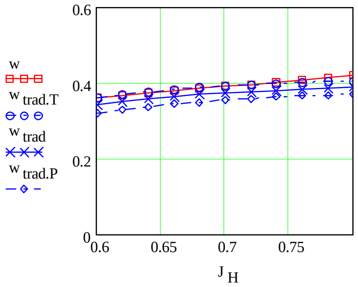
Wake fractions



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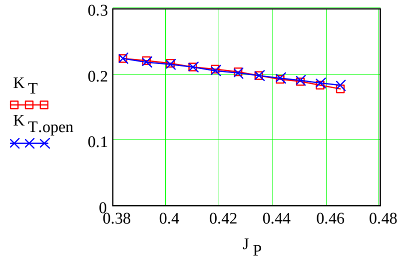
Thrust ratios



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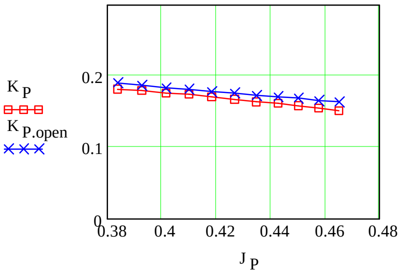
Power ratios $K_P = 2 \pi K_Q$



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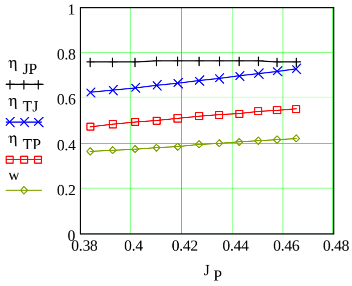
Efficiencies



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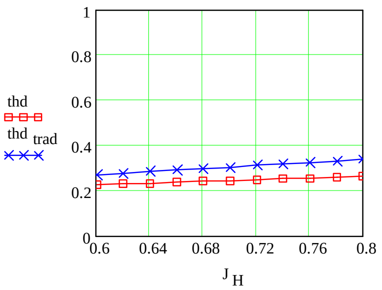
Thrust deduction fractions



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Coherence over all

Thus the coherent model and the coherent set of ***data recorded during a quasisteady model test of only two minutes duration*** permit to identify coherent results in a wide range of propeller advance ratios.

<u>This technique is the only meaningful in case of wake adapted propellers, pre- and post-swirl configurations, partially submerged propellers etc.</u>

The paper of Kooiker and Valkhof is concerned with the importance of coherent measurements in the context of cavitation and pressure fluctuations.

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'Real' advantages

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 'contra' sterns and rudders. Since the war each generation of naval architects has re-invented the idea, but I have not heard of routine applications.

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Some history and …

Horn's early attempts in 1935/37 to overcome the ***deficiencies of Froude's method**** suffered from conceptual limitations and the poor 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.

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… future possibilities

Anybody, not totally blind on both eyes, will see the technological and commercial advantages of the procedure, not even requiring a towing carriage. **Extended experimental studies** necessary for the validation of computer codes and/or optimisations **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. Rapid prototyping, *'printing' hulls*, may provide for future solutions.

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Incoherence

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!***

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Partial similarity

My opinion is that model test should not be performed at slow speeds.

At slow speeds we are picking up more scale effects, than necessary. Accordingly I have evaluated the METEOR model data only at the model service speed.

VWS has carried out some geosim-test series.

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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 have been compared with results of corresponding model tests providing scale effects in wake and thrust deduction fractions, ***for the first time worldwide***.

These scale effects are the corner stones of reliable powering performance predictions.

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METEOR: Test conditions, *1988*

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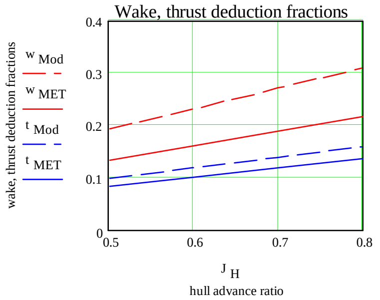
METEOR: Scale effects



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Partially submerged propellers

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.

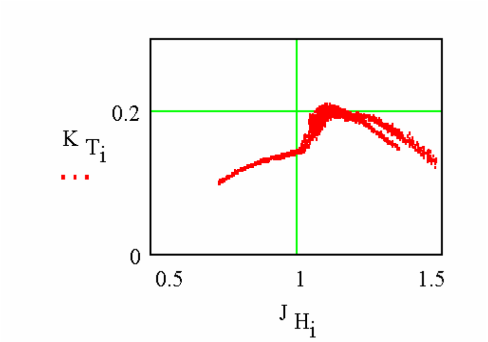
For various reasons the latter are of great interest to Navies. *'Accordingly' there is little published information available.*

Systematic series?

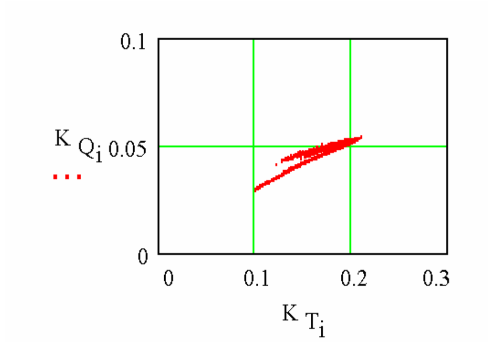
The present and future work and publications of Suresh and Suryanarayana promise to change that situation, although their systematic series is limited to the open water performance.
To my knowledge the question of adequate model-ling has not yet been answered satisfactorily.

The following slides show results of propellers behind the CORSAIR model tested in the large circulation tunnel UT2 of VWS.

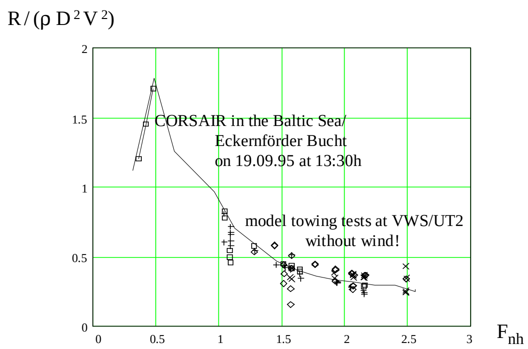
Model $K_T = f(J_H)$



Model $K_Q = f(K_T)$



Resistance: shallow water



Innovative solutions

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 this technique for monitoring and research purposes.

Podded propellers

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 tests *appears* to be adequate.

But, *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.*

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Essential point

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 usually 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 optimum solutions and scaling.***

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Advanced configurations

The <u>solutions so far have been based on the *naive conception* of a propulsor as thruster</u> over-coming the resistance of the hull to be propelled.

<u>In advanced hull-propulsor configurations</u>, maybe pump jets, 'starting' with ducted propellers, **<u>this point of view can no longer be maintained</u>,** ***thrust is no longer a meaningful measure of performance and goal of design.*** *Consequently the concept should better be'deleted from our intellectual inventory'.**

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Propulsors as pumps

An alternative much more adequate and efficient conception is to consider propulsors as pumps *feeding energy into the fluid and establishing the condition of self-propulsion*, vanishing net momentum flow into the hull-propulsor system.

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 suffering from edge singularity.

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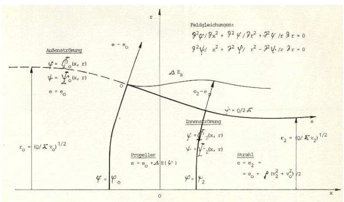
Ideal ducted propeller, *1978*



- 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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Purpose of ducts

The sketch clearly shows that the purpose of ducts is

- *not* to provide thrust
- *but* to avoid edge singularities

and thus <u>*to approach ideal propeller performance*</u>.

Most expositions of the theory of ducted propellers are quite inadequate and misleading, based not on elementary hydrodynamics, but rather on professional superstition.

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Outdated designs

Most design methods are still concerned with ducted propellers in open water. And <u>the methods to deal with hull-propeller interactions are too crude</u>, *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. The following sketch shows the extreme condition

$T_A = T_{AE}$,

$T_D = T_{DE} + t\,T$.

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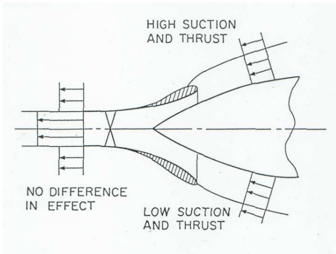
Daniel Bernoulli in action

Suction at the hull and thrust at the duct <u>constitute an energetically neutral hydrodynamical short circuit.</u>

Busmann, STG 1935,

Schmiechen, ONR 1968.



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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,

mass density ρ, volume flow 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' mass flow and 'head' are the same**.

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Performance criteria

<u>The point is not to stare at the short circuit, but at the effect of the propulsor.</u>

<u>Independent of the design</u> are the power ratios:

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

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Comparisons

The performance criteria in terms of powers are particularly important in view of comparison of various configurations as discussed in the proposal by Karimi.

<u>Often decisions are based on inadequate performance criteria and comparison of non-equivalent propulsors</u>. *A historical example is Grim's vane wheel.*

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Opinion changed

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 went back to the description in terms of momentum flows. In my opinion both descriptions have to complement each other if it comes to forces and design for strength.

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Design procedure

A corresponding method for the design of wake adapted ducted propellers starts from the ***condition self-propulsion,*** from the ***effective*** resistance and the corresponding ***net power*** to be fed into the flow.

Usually the constraints on the body contour are too narrow, based on the naiv concept of propulsion. In fully integrated designs the hulls should not be 'stream-lined', 'tapered'!*

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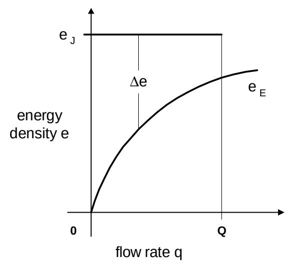
Design goal

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



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Nasty by-product

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.*

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'Pump': stator, rotor, duct

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'Pump': behind *Amtsberg*'s 'cigar'

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Conclusions

Hydrodynamic 'experiments', physical and/or numerical, come in only after a simple hydro-dynamic model **constituting an adequate normative ship theory** has been adopted.

The examples sketched do not solve *all* problems, but are only paradigmatic in character, showing the potential for possible, dramatic rationalisations.

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Anything goes: KISS

Only on this level of abstraction can parameters, performance criteria and development strategies be defined in a professional, efficient fashion.

Feyerabend (1975) in his famous treatise 'Against Method' stated: 'The only general principle, not impeding progress, is: ***anything goes***.'

'Accordingly' I took the freedom to choose the powerful engineering principle:

KISS: ***Keep it simple, stupid .***

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Power tools: ***take advantage***!

The 'only' question left is:

What can and what needs to be done next?

Take competitive advantage of the concepts and power tools provided for the solution of other problems at hand, typically the design and evaluation of efficient research strategies and test techniques, the design of appropriate facilities, the construction of adequate performance criteria etc etc.

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