Controllable pitch propellers for future warships and mega yachts

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1. Abstract
This paper intends to give a short impression of the design process of a wake adapted propeller and a short historical development of the mathematical models. It discusses the possibilities and the boundaries of the hydrodynamic propeller design. The blade strength must be also considered in this process and in our opinion it should be done by current possibilities. We check the design considering the rules of classification societies and add a finite element approach. This is an important tool to analyze the fatigue of blades and components of the controllable system.

This paper recommended some values of sensitive boundaries for propeller design constrains, because the wake field and the ship structure are the given boundaries for the design process. A propeller designer has to use the full potential of the boundaries in order to fulfill currently expected specifications of high end projects like navy ships and mega yachts.

1.1. Keywords
propeller design, pressure fluctuation, FEM

2. Introduction
For many decades Andritz Hydro (formerly known as Escher Wyss) has been designing controllable pitch propellers (CPP) for different ship types each with specific requirements. Our customers are located worldwide. The field of application, where Andritz Hydro has a considerable experience, are navy ships, such as minesweepers, corvettes, frigates and landing ships, but also mega yachts. These applications have a high level of design constrains with very stringent limits. Of course, Andritz Hydro is also able to design and produce CPP solutions for merchant ships like container ships, bulk carriers etc, which are carefully adapted to the specific requirements of their propulsion behavior.

The challenge for the propeller designer is to meet the following requirements:

- propulsion efficiency
- cavitation behavior
- pressure fluctuations
- acoustic signatures
- the number of revolutions at specific power

This overview presents today’s possibilities to meet the design targets and gives an outlook to the next generation of CPP designs. The standard design work is usually based on our own proven propellers or will be derived from the Wageningen propeller series. For special requirements these methods are not sufficient. Lifting line/lifting surface theory, boundary element methods and Reynolds Averaged Navier Stokes Equation Solvers are the proper tools for enhanced designs.

Andritz Hydro has been a member of the “University / Navy / Industry consortium on cavitation performance of high speed propulsors” for a long time and participates in the continuous development of mathematical methods for computational fluid dynamics. Therefore, we have much theoretical and practical experience in the field of pressure fluctuations at the ship hull. The presentation shall give an impression of our design procedure and of the design constrains as well as of the excitation level on ship structures in the past and near future, as expected by us.

Furthermore, the presentation gives a short impression of our precise manufacturing of CPPs, i.e. the CNC – milling of blade surface, the possibility of manufacturing of air ejection channels and the high standard of our quality management. These methods offer a variety of new possibilities and we are able to satisfy all necessary and special requirements of navy ships and mega yachts. Nevertheless, model tests at correspondingly equipped model basins are strongly recommended by Andritz Hydro.

The following text and figures will explain the above mentioned topics.

3. Design process hydrodynamics
The design process of controllable pitch propellers starts typically with an investigation from our own proven propeller series. The required information of this work are the ship data:

- power
- number of revolutions
- dimension of ship hull
  (e.g. length, breadth, block coefficient etc.)
and the hydrodynamic propulsion coefficients such as:

- wake fraction
- thrust deduction
- relative rotative efficiency
- as well as data of the stock propeller

The results of our approach are the main parameters of the propeller. These global data are the starting point of wake field adapted propeller. At this point it is necessary to get the wake field and all information of the ship hull, because our next step is an adaptive wake field propeller by means of a vortex lattice method.

In the past the wake field adapted propeller had than all relevant main parameter and the section design was limited to the chamber and pitch distribution which was two dimensionally with lifting line methods. At the moment, we start the optimization from this main parameter, check the design three dimensionally and optimize all propeller parameters, starting with the global parameters down to the local ones.

The most promising designs from the vortex lattice method are recalculated with a boundary element approach. It makes sense to enhance the accuracy of the results by means of the boundary element method, but additionally for few projects it is necessary and possible to recalculate of the propeller project with RANSE – Solver. But the preparing and calculation time is increase. With nearly all projects, model test are carried out in a reputable model basin.

3.1. Wageningen B-Series supplemented by our own previous propeller designs

At the moment we use the Wageningen B-Series at project state. This data is the best and fastest possibility to get a first indication of the main propeller parameters. It is possible to check the principal feasibility of the project and we are able to advise and give recommendation to our customers in their projects.

There are a few drawbacks of the Wageningen B-series for today’s projects:

- The low skew is not up-to-date, we produce currently propeller with nearly 50° of skew
- The constant pitch distribution ratio
- The restricted pitch ratio

The wake adapted propeller has a variable pitch distribution and a higher pitch ratio than the Wageninen B Series. Some navy propellers have pitch ratios greater than 1.6 which can not checked with the Wageningen B - Series.

At design process this result with our own thoughts represents a domain where we are looking for the optimum propeller. We select one of our designed propellers from our stock with the corresponding main parameter or create a “standard” Andritz Hydro (Escher Wyss) propeller, by means of the lifting line/surface method.

3.2. Vortex lattice method

As a next step we use the vortex lattice method (MPUF from University of Texas) as our fastest possibility in order to check the hydrodynamic behavior of the propeller design, by checking the propeller efficiency and the cavitation behavior in a three dimensional way. The accuracy of the results is quite good, but does not always meet the specified values. The results are sufficient and suited for comparisons of designs and give a good impression of the capability and hydrodynamic behavior of the propeller. This way we check, compare and decide on all main parameters:

- Number of blades
- Area ratio
- Pitch ratio

Once we have one or several possibly good solution(s) we can start with detailed optimization of

- pitch distribution
- chamber distribution
- rake distribution
- skew distribution
- thickness distribution

The results of the optimization are one or perhaps several good wake adapted propeller(s). Some years ago, the propeller design was finished here. Then the designer decided which propeller was the best compromise of efficiency, cavitation behavior and pressure pulses. Nowadays, we make one step forward with the next mentioned topic.

3.3. Boundary element method

The boundary element program (PropCav from University of Texas) enhances the accuracy of the hydrodynamic results. But on the other hand the calculation time increases. The preprocessing time approximates the same size as the vortex lattice method, but the calculation time increases.
is much larger. Therefore at Andritz Hydro we make the global investigations with the vortex lattice method before we start with the boundary element method. At this step of the propeller design we make only small changes to:

- propeller area ratio
- global pitch ratio,

because they are nearly fixed. The optimizing of detail parameters are continued with the following parameters:

- pitch distribution
- chamber distribution
- rake distribution
- skew distribution
- thickness distribution

The boundary element method represents the best compromise between calculation time and accuracy of today’s methods. The comparison with model tests has reached a high degree of agreement and the calculation results confirm the above mentioned hydrodynamic characteristics like efficiency, cavitation behavior and pressure pulses. Nearly all of our projects can be terminated with the verified first design, which we had been delivered to the model basin for testing the propulsion and cavitation behavior. At the moment we are able to present optimal propeller geometry in a pretty short time after having received the input data. This can be achieved by the integration of vortex lattice method and boundary element methods at the design process.

Nowadays the estimation of underwater noise is not possible, also not with a boundary element method. Andritz Hydro will start a research study with RANSE solver coupled with acoustics software, because the underwater noise gets more and more important.

3.4. RANSE (Near Future)

Reynolds Average Navier Stokes Equations Solvers have reached an attractive high level of quality and acceptable time consumption. For the near future Andritz Hydro plans to calculate with a RANSE - solver the propeller open water curves, propeller cavitation in homogeneous and inhomogeneous flow. A previous study showed that this approach is promising. Figure 3 from this study represents the propeller open water curves from a model test in comparison with results obtained with the commercial RANSE solver ANSYS CFX.

![Figure 2 Pressure distribution and cavitation of a mega yacht propeller calculated by means of the boundary element method](image)

![Figure 3 Propeller open water curves CFD versus model test results](image)

![Figure 4 Stream lines of a CFD calculation of a five bladed propeller](image)
The advantage of the Reynolds Average Navier Stokes Equation Solver in comparison to programs based on the lifting line theory, respectively boundary element method is the possibility to solve off-design operations and detached flows. These items become more and more interesting.

Additionally, the coupling of noise software with the Reynolds Average Navier Stokes Equation Solver is possible and seems to allow the identification of sources of flow induced noise, which is the first step for good and comparable results.

4. Blade strength calculations
The calculation of the blade strength forms an integral part of the hydrodynamic design. The blade thickness is usually calculated according to the rules of a classification society and additionally tested by finite element approaches. The finite element approach has a high level of automation and can be done after each relevant hydrodynamic blade calculation without loss of time.

The rules of recognized classifications society are well known, therefore in this context will be discussed only the finite element approach.

The propeller blade experiences at each position in the wake field at different flow conditions. The blade thrust during one revolution is presented in Figure 5.

![Thrust of a blade at one rotation](image)

Figure 5  Thrust of a blade of a twin screw ship during one revolution

The relevant positions depend on the wake field. In this case the characteristic angles are the maximum at 156°, the minimum at 24°, the thrust curves intersects the mean thrust of about 67 kN at 120°, 192° and touches at about 205°.

The load distribution is assigned to a hexagonal grid and the commercial finite element solver ANSYS calculates the von Misses stresses. The evaluation of product life time is done by means of the Haigh – diagram, which is presented at Figure 6.

The abscissa represents the corresponding average stress $\sigma_{\text{mean}}$ and the ordinate the stress amplitude $\Delta\sigma$.

The lines with $X = \text{value}$ has constant values (Formula (2)) at different average stresses. The safety against collapsing is the distance between operation point and boundary of material. The lines from A, B and C are the boundary curves of different propeller material.

The safety against fatigue can be calculated by the distance between point of origin and crossing point of constant line and the distance between calculation point and point of origin.

![Haigh - Diagram](image)

Figure 6  Haigh diagram

The Figure 7 explains the stress fluctuation, which we derived by a finite element approach. The formula (1) calculates the amplitude for the ordinate and number (2) helps to indicate between which constant lines we are.

\[
\Delta\sigma = \sigma_{\text{max}} - \sigma_{\text{mean}}
\]

\[
X = \frac{\sigma_{\text{max}} - \sigma_{\text{mean}}}{\sigma_{\text{mean}}}
\]

![Evaluation of stresses for Haigh figure](image)

Figure 7  Evaluation of stresses for Haigh figure

5. Wake field
The wake field is the most important constraint for the propeller design. We distinguish between single and twin screw wake fields. All other arrangements can be reduced to these two types. In the most cases the single screw wake field is less favorable than a twin screw wake field because:

- The wake peak is larger
- The difference between maximum and minimum wake fraction is greater at the same radius
- The velocity gradients are greater
Our recommended values for single screw ships are:

- The difference between maximum and minimum wake fraction at the same radius should be less than 0.45.
- The velocity gradients should be as smooth as possible.

And for twin screw ships:

- The difference between maximum and minimum wake fraction at the same radius should be less than 0.3.
- The velocity gradient should be as smooth as possible, too.

Nevertheless, Andritz Hydro are able to design a propeller for any given wake field, but the quality of the wake field has a crucial impact on the performance of the propeller. The wake field which is presented in Figure 8 is very good, because it has very smooth velocity gradients and the difference between maximum and minimum wake fraction is smaller than 0.2.

6. Design specifications

In the past the design criteria were “only” the power and the number of revolutions and it was a big challenge to hit the target. Currently the specifications as stipulated by the clients assume that the propeller manufacture disposes of powerful computational tools, so this is no more a big challenge, but it is still a challenge. We are able to reach this target with the first design with adequate tolerance. Nowadays the big challenges for the propeller designer are additional requirements, such as pressure fluctuations, cavitation behavior, efficiency and the noise levels.

The requirements concerning these five points (power, number of revolution, pressure fluctuation, cavitation behavior and efficiency) can be satisfied with today’s computational methods. Mathematical models of the propeller under water noise are currently under development and Andritz Hydro participates in this process, too.

6.1. Power and number of revolutions

Relation between power and number of revolutions are verified at Andritz Hydro by means of a boundary element method. In an early design stage Andritz Hydro computes the propeller behavior with a lifting line program, but every propeller design is finished with the boundary element method approach and the final adjustment is made by this result in order to reach the targets.

6.2. Propeller efficiency

In the past the optimization of the propeller efficiency was the ultimate aim of the propeller design, but at the moment it is not always the most important target. Frequently other design criteria are of equivalent importance for customers with specific applications like navy ships and yachts. Therefore, we have to aim at the best compromise by minimizing the loss of efficiency.

6.3. Pressure fluctuation

Specifying pressure fluctuations is common practice since the nineties (in our orders). In order to find a trend for the specified limits of the pressure fluctuations we analyzed the technical specifications of our orders. However, this analysis gave no evidence of the systematic development of pressure fluctuation of the first and second harmonics, but indicated a minimum value of the first and second harmonic of yachts and navy vessels. The yacht projects have reached a minimum value of 1 kPa for the first harmonics and 0.7 kPa of the higher harmonics. The limit for navy vessels is 2 kPa for the first harmonics and 1 kPa the higher harmonics. Andritz Hydro complies successfully these requirements. The higher value of navy vessels is attributed to the significantly higher power concentrations.

This is only possible, if the customer provides a good wake field and an adequate tip clearance. Furthermore, Andritz Hydro can supply propellers with an air emission system. The advantage of an air emission system is the possibility to reduce the noise emission. Figure 9 shows the test of a propeller blade with air emission.

6.4. Cavitation behavior

The investigation of the cavitation behavior begins with vortex lattice method and ends with the boundary element method. The target is a stable and non erosive cavitation at the suction side and no pressure side cavitation at the blade surface. At the root section any cavitation has to be avoided. Should it be unavoidable, in any case a well-balanced suction and pressure side cavitation has to be aimed at. The area of cavitation has to be as small as possible. A small and fluctuating cavitation volume is instable and tends to be erosive. On the other hand a
7. Manufacturing of propeller

Andritz Hydro are able to finish premachined casting parts in our work shop with CNC controlled equipment like for example a five axis milling machine.

Figure 9  Testing the air emission of a navy vessel

Figure 10  High skewed propeller blade for a mega yacht

The dimensions of our five axis machine allow a blade size up to six meters height. There are no restrictions in blade area, skew and rake.

The manufacturing method of the air emission system is unique and does not constitute any restriction for the hydrodynamic blade design. It is not necessary to increase the thickness of leading edge.

The computer aided manufacturing is based on our three dimensional solid, which we define with the computer aided design tool Unigraphics NX 4.0.

8. Summary

We are able to design and produce propellers, which satisfy all today’s requirements. We reach this target in the most cases with the first design. Nevertheless, in our opinion it is highly recommended to confirm the design in a recognized model basin. The mathematical models are approved and lead to satisfactory good agreement with the model tests. As a rule the first design meets the clients’ requirements and, usually, a second attempt is not necessary.

The design philosophy has moved from two dimensional to three dimensional approaches. Since the global propeller parameters are not fixed after the first investigation, they have to be subjected to our optimization process, where the propeller is finally adapted to the wake field. That means that each of our customers gets a tailor made propeller based on our customers’ requirement such as:

- Pressure pulses
- Cavitation behavior
- Cavitation inception speed
- Efficiency

The future will face us with more and more off design conditions and the influence of underwater noise requires more and more attention.

9. References


stable and large cavitation area has a detrimental effect on the pressure fluctuations and propeller efficiency.