Second International Symposium on Marine Propulsors
smp'11, Hamburg, Germany, June 2011

The Marine Propeller Design Spiral

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ABSTRACT

A marine propeller blade design, similar to ship design in general, represents a compromise that accounts for several, often contradicting requirements. Therefore, a so-called "design spiral" is followed in the design process, starting with a basic design that satisfies the most basic requirements, checking its different aspects (efficiency, strength, cavitation), improving it gradually and repeating the appropriate calculations. In the beginning, the methods involved are simple in order to make quick progress, but they become more sophisticated towards the end of the design in order to accurately evaluate the critical properties of a design candidate.

This article outlines how this design principle is applied to marine propeller blade design and how modern design and analysis methods like numerical optimization and computational fluid dynamics can be incorporated.

Keywords

Propeller Blade Design Procedure Methodology

1 INTRODUCTION

The propeller design usually starts with determining the main particulars (diameter, mean pitch, blade area) and an initial estimation of attainable efficiency based on design charts or previous systematic calculations. A first, blade strength calculation is done according to classification rules. Lifting-line theory can then be applied to determine the radial distributions of pitch and blade section cambers. A subsequent calculation of two-dimensional cavitation buckets for a number of radial stations provides further information about cavitation performance and suitable blade width. A strength assessment based on beam theory and hydrodynamic calculations based on lifting surface theory or boundary element methods serve to refine the design. Later in the design process, blade strength should be checked by finite element analysis and hydrodynamic calculations should be extended for off-design conditions. Each loop can be repeated several times in order to not only determine more precise, converged values but also to numerically test different load distributions. Automatic optimization loops follow this principle as well until the "optimum" compromise (or a "Pareto front" of suitable design candidates) has been evaluated.

The "optimum" design candidate and its performance may be verified by means of viscous flow calculations (which may in the future become a further loop of the design spiral) and scale model tests (which have in the past sometimes been repeatedly performed). However, the final confirmation of success will be obtained not earlier than during sea trials and after a certain period in service.

2 PROPELLER DESIGN TASK

The propeller design task can be regarded as an optimization problem with several constraints (like maximum diameter). Although some constraints are requirements, they have to be completely fulfilled; otherwise a design candidate is declared "non-feasible". One example for such a constraint is sufficient strength. Other, often contradicting requirements are subject to "free" optimization, like efficiency or vibration excitation level. Depending on customer expectations, a certain level of efficiency might be declared "non-suitable", even if it represents the physical optimum.

2.1 Propeller Working Conditions

The propeller working conditions are defined by the application (i.e., the ship's wake field, the ship's thrust demand as a function of speed, engine power and shaft speed, shaft immersion, and available space). Generally, the propeller working conditions are fixed once the ship and machinery are defined. In exceptional cases like high-powered fast craft, the interaction between propeller and hull can become strong enough to influence the propeller working conditions. Changes in propeller diameter or blade load distribution are known to also have an effect on propulsive coefficients. RANS methods modeling hull and propeller can be employed for the determination of propeller-hull interaction. However, due to limited resources, this "complete" approach is not yet taken on a regular basis.

In favorable cases, the propeller designer is involved in the early ship design stage. The perfect match of hull and appendage design (resistance, quality of wake field), machinery (main engine power and load limit curve, gear box reduction ratio, shaft diameter), propeller (size, number of blades) and their arrangement (clearances) is at least as important as the individual optimization of single components. This especially counts in complex design tasks (e.g., high power density or high requirements on noise/vibration levels). On the contrary, there are no such opportunities in propeller designs for refit / upgrade projects where only individual components are replaced.

Today's highly sophisticated engines have a sharply defined nominal shaft speed at which the nominal power is available. Therefore, one important constraint for the propeller design is to ensure that it absorbs the specified power at exactly the specified shaft speed.

2.2 Basic Design Requirements

The most basic and the most important design requirement is sufficient strength, not only of the blades, but also of the hub (transmission of driving torque from the shaft to the propeller). The blades have to withstand hydrodynamic forces (thrust, torque) and mechanical forces (centrifugal forces, external forces like ice loads). Due to the inhomogeneous ship's wake field, the hydrodynamic forces are unsteady. Therefore, blade stresses due to hydrodynamic and centrifugal loads under normal operating conditions have to be compared with the propeller material's fatigue stress properties. On the contrary, blade stresses due to single or seldom occurring load peaks may be compared to yield strength.

A second very important requirement is the absence of erosive cavitation patterns. Very often, cavitation cannot be completely avoided. However, the designer has to ensure that the cavitation remains "harmless". Cavitation induced erosion can cause blade failure. Therefore, the risk of erosion must be considered as carefully as blade strength.

A further prominent design requirement is efficiency. It is not only affected by the propeller working conditions (especially by thrust loading), but may also be restricted by other requirements like vibration excitation and noise levels (propeller-induced hull pressure pulses, unsteady shaft forces, radiated noise) or limited propeller weight.

2.3 Other Design Requirements

All the above listed requirements may have to be considered under several different operating conditions. The propeller's power absorption and efficiency vary with the ship's loading, hull surface condition, trim, and sea state, which results in more than one "propeller curve" (Figure 1). Cavitation and its effects depend on shaft immersion and thrust loading. Propellers in multiple-shaft configurations might be operated with different loadings. This is why any propeller should show a "forgiving" performance under off-design conditions. A design optimized to the maximum according to a set of requirements might be subject to unforeseen operating conditions. In such a case, extreme designs often clearly show adverse properties, making them less suitable for "real world applications". One way to avoid this situation is to consider additional, slightly more severe working conditions during the design.

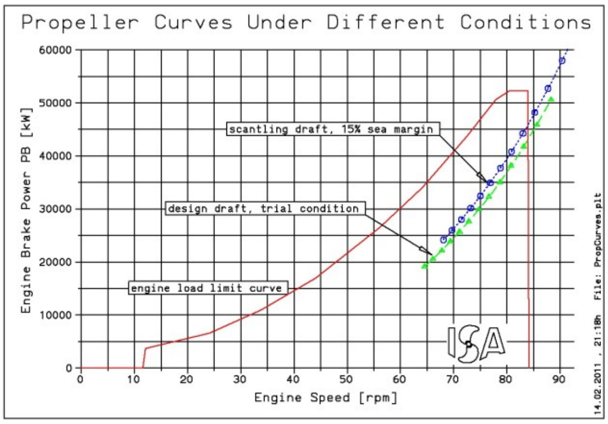

Figure 1

3 PROPELLER GEOMETRY MODELLING

3.1 Two Ways to Define a Blade Geometry

There are principally two ways to tackle the propeller blade design task. One is to specify a pressure distribution and to evaluate the corresponding blade geometry. The other one is to generate a blade geometry and to evaluate the resulting pressure distribution.

In the author's opinion, the former is less suitable for applications with a number of different working conditions, and it bears the risk of generating irregular geometries in a strongly inhomogeneous wake field, whereas the latter offers greater flexibility and easier handling. This paper refers to the strategy that the designer generates or modifies a blade geometry and subsequently evaluates the resulting performance.

3.2 Parameterization

The final blade geometry needs to be defined in every detail in order to ensure that the manufacturer understands exactly what to do. However, it is useless to model the blade in every detail in an early design stage when even the main particulars like diameter or blade area still have to be determined.

Therefore, it appears reasonable to use only a few "parameters" in the early design stage and to add more parameters during the course of the design. For example, it is sufficient to select just four parameters (diameter, number of blades, blade area, mean pitch) to define a Wageningen B-series propeller (the detailed blade geometry is then determined according to the description of the model propellers tested).

Depending on the complexity of the design task, more parameters are needed in order to adapt the blade design to the specific requirements and working conditions. In a first refinement, additional parameters may define the magnitude of skew and rake, blade thickness, and profile section camber. In a second refinement, the radial distributions of the above may be parameterized, allowing the designer to optimize the blade shape and radial load distribution. In further refinements, additions for the section profile types like leading edge radius, trailing edge thickness, and chordwise positions of maximum camber and maximum thickness may be introduced.

In a "manual" approach, the designer can separately determine each of the characteristics listed above. This involves fairing in radial and circumferential directions. Modifications in order to avoid irregular surfaces (waviness) would be cumbersome.

It is far easier to define a small set of suitable functions and the corresponding parameters. For example, it (generally) appears not suitable to define the skew distribution by ten radial stations. Such a fair curve can very well be expressed by as few as two parameters: "total skew" and "polynomial degree of the curve".

A second approach is to use functions and parameters not for the complete definition of a new design candidate, but only for the modification / distortion of a "parent" design. Here again, one has to take care that the modifications do not result in an irregular surface.

Parameterization not only greatly reduces the number of data; it also facilitates modifications and optimization, while satisfying the need for a fair surface (as long as the defining functions have been well conceived). However, one should bear in mind that this approach implies that the functions and parameters restrict the attainable diversity of the solution space. For example, the above proposal of just two parameters for the skew distribution excludes all alternatives with an S-shaped distribution. This may be desirable in the sense of ensuring a smooth surface, but it might also restrain an optimization procedure from finding innovative, truly optimum solutions. Therefore, it is up to the designer to ponder what kind of functions and how many parameters he should employ for the task at hand.

4 DESIGN SPIRAL

There are numerous methods available to determine a design candidate's performance, differing in prediction accuracy, complexity, computational effort, and amount of required input data. In case of repeated, only slightly differing design tasks, one might take over a lot of data from previous, successfully finished projects, making use of the experience gained in order to have a "head start". The more common case is to use simple methods first in order to get a rough idea of propeller main particulars and performance, and to refine the design by more sophisticated methods in a later design stage.

In the following, each level of accuracy / complexity is considered as a loop in a spiral which eventually leads to the final design. Each loop comprises prediction methods for efficiency, cavitation and strength. The results obtained in each loop are assessed to update the design candidate's properties accordingly.

4.1 First Loop of the Propeller Design Spiral

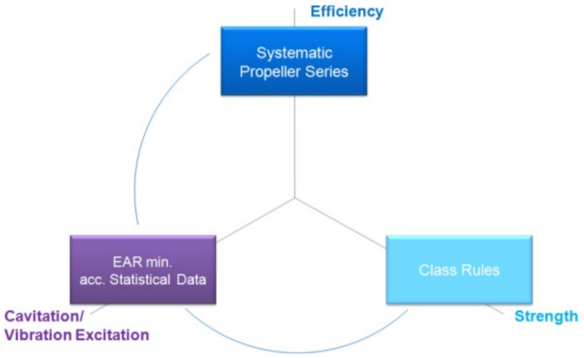

Figure 2 – First Design Loop

The propeller design usually starts with the determination of main particulars (diameter, mean pitch, blade area). The optimum diameter and the suitable mean pitch are evaluated on the base of systematic model test results (e.g., van Lammeren et al 1969) or systematic numerical predictions, aiming at maximum efficiency for the given thrust demand. The efficiency determined can be used to check the attainable ship speed with the specified shaft power. The required blade area (depending on the diameter) is estimated by use of statistical or semi-empirical data (e.g., Burrill & Emerson 1962-63) or according to experience. Based on these main particulars, a first blade strength calculation is done according to classification rules, resulting in a blade thickness curve along the radius.

4.2 Second Loop of the Propeller Design Spiral

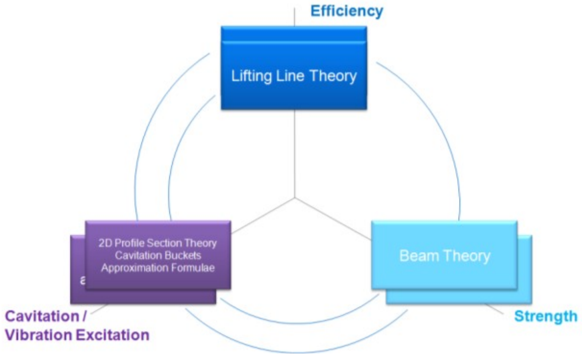

Figure 3 – Second Design Loop

Lifting line theory (e.g., Lerbs 1955) is applied to determine the radial distributions of pitch and blade section cambers and to update the predicted efficiency. A subsequent calculation of two-dimensional cavitation buckets (Brockett 1966) for a number of radial stations provides further information about cavitation performance and suitable blade width. The strength assessment can be refined by the application of beam theory (e.g., Conolly 1961) (updating blade thickness values).

4.3 Third Loop of the Propeller Design Spiral

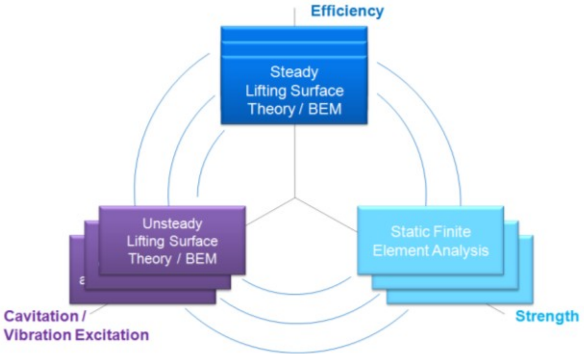

Figure 4 – Third Design Loop

More accurate hydrodynamic calculations are based on lifting surface theory (e.g., Greeley & Kerwin 1982) or boundary element methods (e.g., Kerwin et al 1987) (updating blade width, pitch, and camber values). Similarly, blade strength analysis by means of finite elements is used to determine more precisely weak points or excess material. In this stage, the hydrodynamic calculations should be extended for off-design conditions (if any). With the power of modern personal computers, this loop (as well as the previous ones) can be repeated several times in order to not only determine more precise values but also to numerically test different load distributions.

4.4 Final Loop of the Propeller Design Spiral

Before being built and taken into service, the selected design candidate and its performance may be verified by the most accurate and reliable methods available and suitable. Viscous flow simulation methods have matured to a degree that they can be employed as a final check. Steady RANS methods can predict the propeller's powering performance, possibly including propeller-hull interaction effects, as well as the scale effects to be expected in model tests. Unsteady multi-phase simulations can predict cavitation performance, possibly including the risk of cavitation-induced erosion. Dynamic finite element analysis may be employed for a detailed survey of fatigue strength or (in conjunction with large eddy or direct simulations) of fluid-structure interaction.

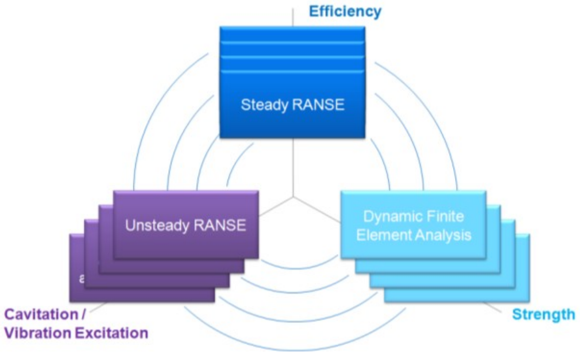

Figure 5 – Fourth Design Loop

With the computational power to be expected for future computers, viscous flow computations may soon become a further loop of the design spiral and within an optimization procedure. This would also necessitate robust and versatile grid generating methods.

Nonetheless, due to neutrality and reliability concerns, scale model tests are still regarded as the ultimate validation (in the field of hydrodynamics) before proceeding to the production of the full scale propeller.

However, the final confirmation of success (i.e. customer satisfaction) will be not obtained earlier than during sea trials and after a certain period in service.

5 PROPELLER DESIGN OPTIMIZATION

Manual as well as automatic optimization loops follow the above outlined principle as well. One or more of the above outlined loops is repeatedly executed until the "optimum" has been evaluated.

An optimization loop begins with the blade geometry generation / modification for one or more design candidates. Initial candidates may originate from former manual attempts or may have been randomly generated. Each candidate needs to be analyzed in order to evaluate the properties (efficiency, cavitation, strength) under all working conditions under consideration. The important part of the optimization process consists of an automated assessment (ranking and selection) and a strategy how to develop new, more "successful" design candidate(s) for the next optimization loop.

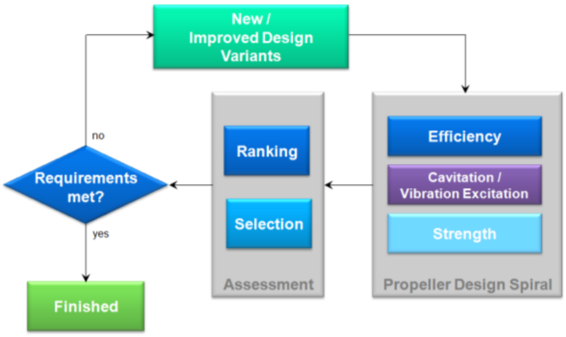

Figure 6 – Optimization Loop

In case of several contradicting requirements, it is not easy to clearly define the term “optimum”. There may be several design candidates who all are suitable, but each of them has its own strengths and weaknesses. This situation can be illustrated in a “Pareto front” diagram which can support the (possibly subjective) decision which of the candidates shall be selected as the “best” compromise.

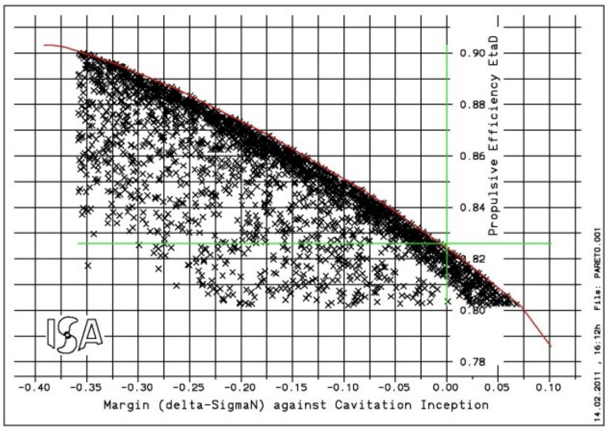

Figure 7 – Pareto Front

There are different optimization strategies around, such as gradient search, expert systems, and genetic algorithms.

Gradient search methods find a local optimum which is not necessarily the same as the global optimum (“running up the first hill won’t lead you to the highest crest of the mountains”). This handicap can be circumvented by beginning the same task from different starting points. However, this means a multiple effort with uncertain success which overwhelms the initial straight-forward approach.

Expert systems are aiming at fast progress based on implemented rules (“if this is the problem, try that”) based on physics or experience. This way, non-promising candidates shall not even be generated, sparing the effort for their assessment. The quality of optimization results strongly depends on (and is limited by) the implemented rules. To the author’s experience, an expert system is less suitable for complex tasks with several propeller working conditions and contradicting requirements, and it might also stick to a local rather than a global optimum.

Genetic algorithms have been successfully used for numerous technical optimization problems. The drawback of high computational effort is often compensated by the method’s robustness and capability to find the global optimum even for difficult response functions. The method may also serve to reveal any weakness within the optimization process because it will sooner or later make use of any means leading to improved prediction results, be it realistic or unrealistic.

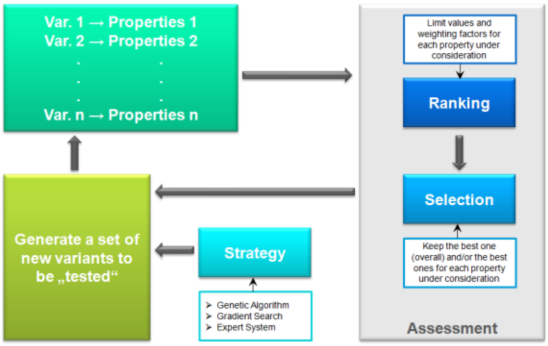

Figure 8 – Optimization Process

6 CONCLUSIONS

In times of ever more powerful computers and ever more sophisticated simulation techniques, this paper describes how less complex methods can contribute in approaching the “optimum” design candidate faster and with less effort. Four loops in a so-called “design spiral” with increasing complexity are described, leading to a gradually refined and improved propeller design. Further loops with increased complexity, accuracy and computational effort may be added in the future in order to account for more difficult problems like propeller-hull interaction, cavitation-induced erosion or fluid-structure interaction effects. The author also presents his views on reasonable design goals and robustness as opposed to sharp optimization strategies.

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