WORKING PAPER

DESIGN OF THE WAGENINGEN F-SERIES

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1 SUMMARY

The Maritime Research Institute Netherlands (MARIN) has started a Joint Industry Project (JIP) to develop a new standard series of fixed-pitch propellers (FPP) that represent contemporary propeller designs: the Wageningen F-series. The primary objective is to provide the maritime industry accurate, realistic and competitive efficiency levels balanced against common cavitation, noise and vibration requirements. The F-series will provide performance data in all four quadrants for each propeller of the series.

For each of the 150 F-series propellers a design condition was defined. The design conditions are both realistic and evenly distributed across the F-series matrix to represents typical ship types. As a design philosophy, the aim was to have a smooth input in order to achieve a smooth output as well.

State-of-the-art software tools were applied in the design stage of the project. A multi-objective optimisation tool was used with the Boundary Element Method (BEM) PROCAL. The best propellers in terms of efficiency, cavitation (erosion risk), hull-pressure fluctuations, noise levels and strength of the tip-vortex cavitation were smoothed into the series.

The design of the F-series was approached as an iterative process between the supplied design input, the description and freedom of the design variables and the optimization results.

The F-series geometry was designed for high efficiency and average comfort levels thereby allowing significant amount of non-erosive cavitation. Compared to the numerical B-series, the performance of the F-series is better both in efficiency, cavitation behaviour and hull excitation.

In summary, the F-series will provide realistic and competitive efficiency levels balanced against common cavitation, noise and vibration requirements. Over time, the F-series is intended to replace the B-series.

2 INTRODUCTION

The Maritime Research Institute Netherlands (MARIN) has started a Joint Industry Project (JIP) to develop a new standard series of fixed-pitch propellers (FPP) that represent contemporary propeller designs: the Wageningen F-series. The primary objective is to provide the maritime industry accurate, realistic and competitive efficiency levels balanced against common cavitation, noise and vibration requirements. In time, it is envisaged that the F-series will replace the B-series.

This working paper elaborates on the design process of the Wageningen F-series.

2.1 Market Developments

The following market developments have led to the initiation for a new series of FPPs:

1. It is expected that FPPs will find wider application with electric drives, that have a much wider operational envelope than the traditional diesel engines. More accurate data is required to assess

the conditions for which traditionally CPPs would be applied, such as fast acceleration and stopping, fast changing of thrust direction and all kinds of manoeuvres.

2. In the scope of reducing emissions, high demands are put on the efficiency of the propeller itself, which are among others expressed in the EEDI requirements under restriction of the Minimum Power Requirement (translated as bollard pull capacity).
3. Requirements regarding in-board (comfort) and underwater-radiated noise (URN) - relevant to the marine eco-system- are becoming stricter.
4. Ship owners more and more require certain efficiency and comfort levels over a larger range of ship speeds.

2.2 B-series History

Developments in the 1930’s lead to the design of propellers with wide blade tips, circular back sections on the outer radii, and airfoil-shaped sections on the inner radii. Propellers of this type were called B-series propellers. The B4-40 propeller series was designed first and the series was gradually extended with larger blade area ratios and various blade numbers, until it reached its final volume of 23 propeller types, ranging from B2-30 to B7-85, containing altogether about 130 propellers.

The measurements of the B-series propeller characteristics were performed over a period of about 30 years. Over this time span measuring techniques and propeller model manufacturing accuracy improved. In addition, tests were not always carried out at the same rotation rate, that could be as low as 300 RPM for some propellers. In the 1970s all B-series data have been corrected to a level corresponding to a Reynolds number (Re) of $2 \cdot 10^6$ (Re defined on the blade section at 0.75R). Basically these are the data that have been used worldwide since. In [Kuiper, 1992], the complete B-series data have been published and a useful overview of publications about the B-series has been provided.

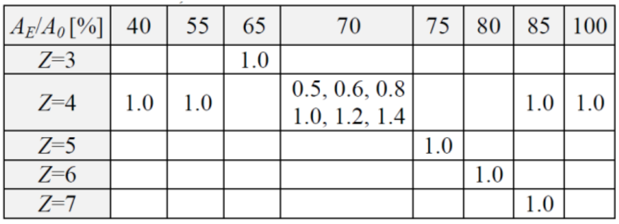
2.3 Accuracy

Nowadays, however, there is increasing need for more accurate data, also in off-design conditions. Besides the current highly accurate production methods, also the testing procedures are automated with the Quasi Steady Open water (QSO) method such that the measurement of the full quadrant performance can be quickly done [Dang et al, 2013].

2.4 Completeness

The four quadrant measurements of the B-series are not complete, as indicated by Table 1. The off-design performance of some of the propellers depends heavily on extrapolation methods.

Table 1: P/D of B-series propellers with four-quadrant open water characteristics



A_E/A_0 [%]	40	55	65	70	75	80	85	100
Z=3			1.0					
Z=4	1.0	1.0		0.5, 0.6, 0.8 1.0, 1.2, 1.4			1.0	1.0
Z=5					1.0			
Z=6						1.0		
Z=7							1.0	

The four-quadrant performance will be measured for each of the new F-series propellers.

2.5 Contemporaneity

Traditionally, the performance data of the widely used B-series propellers are used in the early design stages of ships and propellers. The efficiency of B-series propellers is good, but their design does not particularly take into account other aspects of FPP performance -like hull pressures, noise and cavitation erosion- that have become more and more important over the years.

Therefore, the efficiency of the propellers of the new F-series should reflect the best achievable level, while the requirements on cavitation (erosion), propeller-induced hull-pressure fluctuations, noise and inception of tip-vortex cavitation were taken into account in the blade designs.

For that reason, contrary to the B-series, the F-series propellers vary systematically and smoothly in the radial distributions as a function of the main parameters, such that each propeller within the F-series approaches contemporary industrial designs. This approach was also used in the development of the Wageningen C- and D-series [Dang et al, 2013].

3 F-SERIES DESIGN PHILOSOPHY

3.1 Main Parameters

The F-series is defined in three main parameters:

1. Blade number Z, ranging from 3 to 7.
2. Pitch, defined as the pitch over diameter at 70% of the radius, denoted as PD, ranging from 0.6 to 1.6 in steps of 0.2.
3. Blade Area Ratio (BAR), defined as the expanded BAR, or the Ae/Ao. Five propellers with different BAR are defined for each combination of Z and PD, ranging from 0.3 to 1.1 for the 3-bladed propellers and 0.5 to 1.3 for the 7-bladed propellers.

The BAR of the F-series is not defined with constant step, but by constant factor, putting relatively more focus on the propellers with lower BAR where the performance changes more rapidly compared to the higher BAR propellers.

3.2 Design Hypothesis

It was hypothesized that for every combination of Z - BAR - PD there is one representative ship type on which such a propeller would be used. Nonetheless, database research showed that for container ships and cruise ships, both the 5-bladed propellers coincide at PD = 1.0, BAR = 0.6 and the 6-bladed propellers at PD = 1.1 and BAR = 0.8. In addition, design studies for these ship types indicated that these propellers differ fundamentally in the radial distributions. Therefore it was decided to create two complementary series. The large series of 150 propellers form the F-series, while a smaller series will be created later as a comfort line.

F-series	FC-series
Highest efficiency while complying to cavitation erosion and hull excitation criteria Merchant vessels	Balance of efficiency and tip-vortex noise without sheet cavitation Cruise vessels, yachts, research vessels

It was decided that the F-series would be made first, after which the FC-series would follow. This working paper only considers the F-series.

3.3 Design Conditions

In order to compute the performance, a design condition needs to be defined as basis for the computational evaluation for each combination of the main parameters. The design conditions should be both realistic and smoothly distributed along the F-series matrix.

As a design philosophy, the aim was to have a smooth input in order to achieve a smooth output as well. The input was prescribed for each combination of PD, BAR and Z. The data was based on the analysis of typical ships, after which it was smoothed and interpolated during the iterative process in the design optimization cycle.

The combination of a prescribed thrust loading coefficient C_T, cavitation number σ_N, tip speed λ and diameter D provides sufficient information for the operational condition. Also the wakefield in which the propeller operates was provided. Moreover, to compute the hull excitation a clearance between the hull and the propeller tip was specified. Finally, the astern torque ratio is required by the DNVGL classification rules for propeller strength. The itemization below considers each aspect in more detail:

- Propeller computations were performed by iterating the ship speed towards a prescribed thrust loading coefficient C_T. It was found that an optimization at constant J-value tries to minimize K_T to improve efficiency. Also, an optimization at constant K_T tries to maximize J-value to improve efficiency. Optimization for C_T ensures optimization for efficiency at a realistic operational condition, without compromising the optimal radial distribution of the thrust.
- Optimization for realistic cavitation behaviour was realized by prescribing the cavitation number σ_N at the shaft. A rather strong dependency on PD was required because the local loading on the blade varies much more at higher PD, compared to lower PD. The variation in angle of attack is generally higher for a propeller with high PD. The cavitation number is also dependent on the blade number. At similar BAR, the cavitation number increases with blade number. This is to account for the difference in the t/c ratio and its corresponding dependency on the margin against bubble cavitation.
- The F-series is a series that is designed for behind performance, explicitly taking the wake of the ship into account. Hence, the behind ship efficiency is optimized, rather than the open water efficiency. Therefore, complementary to the design conditions, the wake fields in which the propellers operate are required as input. Using the same design philosophy as for the other input parameters, a smooth input with respect to the wake fields was also sought. An interpolation matrix for the wake fields was defined using the wake fields of typical ships, ranging from bulkers, through container vessels, submarines and LNG carriers towards patrol crafts. Due to interpolation, some wake fields may not be realistic, however, these wake fields are required for smoothness and also beneficial for the robustness of the F-series designs.
- The tip speed ranges from 30 m/s for bulkers, submarines and LNG carriers towards 50 m/s for fast patrol vessels and fast container ships. The tip speed is important to specify the relation between the hydrodynamic pressure and the hydrostatic pressure.
- The clearance between the propeller tip and the surface above the propeller was defined as well. On that surface, the excitation pressures are evaluated to simulate the forces caused by the propeller on a ship's hull. The clearance is defined as the smallest distance between the propeller tip and the hull above the propeller. The prescribed clearance in the F-series design methodology ranges from 20% towards 50% of the diameter for a patrol craft and a bulker, respectively.
- DNVGL proposed to use a simplified approach to estimate the global response levels due to propeller induced excitation. DNVGL developed an empirical transfer function to relate the excitation force to the reference global vertical vibration in the aft ship. The first harmonic excitation force on the square virtual plane of size 1.5 times the propeller diameter is multiplied by a correlation factor. Hence, vibration is assumed to be linear with the virtual force. The correlation

factor was determined based on the ship type and its displacement. For the F-series this approach was used to interpret the propeller induced excitation using a similar interpolation matrix as the was used for the wake fields.

- The prescription of the astern torque is important for the propeller blade thickness in the area around 0.8R, following from the DNVGL rules. Despite the ambition to allow full torque astern for each propeller in the F-series in view of electric drives, an exception was made for the high BAR propellers and high PD with low blade number. In practice these propellers are generally used for very high powered ships only, which never use full torque astern.

The table below provides a summary of the design parameters. The input and prescribed variables are required to perform the design optimization of the outline of the blade in terms of the chord and skew distribution and the pitch and maximum camber distribution. The rake and thickness follow from the chosen design variables on which they depend.

Input	**Prescribed**	**Design Optimization**	**Dependent**
Thrust loading C_T Cavitation number σ_N Tip speed Wakefield Hull-clearance Astern torque ratio	Hub diameter Chord length at the hub	Pitch Camber Outline (skew and chord)	Rake Thickness (DNVGL)

The hub diameter and chord length at the hub are both a polynomial resulting from the analysis of the MARIN database.

The blade profiles of the F-series are defined as a camber and thickness line for each radius. The most commonly applied blade profiles by the industry are used for the whole series. For the camber, the NACA mean line is selected with a = 0.6 at the hub to delay separation issues and a = 0.8 at 0.6R towards the tip. For thickness, the NACA66 DTMB mod is applied for each radius for which the thickness is applied perpendicular to the chord line.

3.4 Design Process

The design of the F-series was subdivided into four phases:

1. Design studies for typical ships as exploration
2. Optimization for a subset of propellers within the F-series matrix
3. Smoothing of all propellers into one series
4. Details, checks and sensitivities

The design approach was a rather iterative process between the supplied design input, the description of the design variables and the optimization results. The F-series design process is schematically presented by Figure 1.

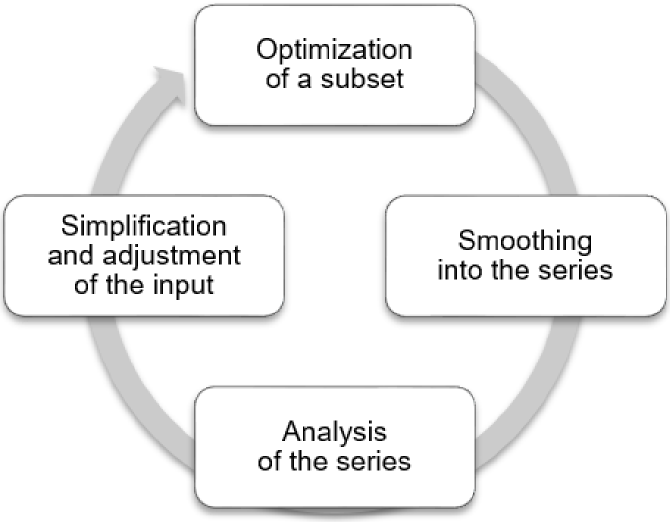


Figure 1: Design iteration loop

In each design iteration the best geometries from the optimizations are selected and smoothed over the main parameters PD, BAR and Z. Subsequently, the input is further adjusted towards better convergence and smoother polynomial-based description of the F-series geometry. High curvature in the polynomial surfaces was avoided for the purposes of consistency and smoothness, which was regarded as more important than the recording of every detail from the individual optimizations.

3.5 Optimization

Multi-objective optimisation techniques provide insight into the various trade-offs between conflicting objectives and indicate the influence of design constraints on the achievable objectives. Objectives and constraints are for instance efficiency, cavitation characteristics, hull excitation or weight. To allow large design freedom, the propeller is fully parameterized in the pitch, camber and outline (both chord and skew) distributions. These are defined as Bézier curves of which the handles form the optimization variables. Within MARIN and the CRS, the multi-objective optimisation method Propagate has been developed for propeller design optimisation studies.

An optimization algorithm controls the computational process and provides input to the geometry generator for a new generation of geometries based on the results of the previous generations. Each propeller geometry is scaled to the correct PD and BAR. For BAR a double iteration loop is used to obtain both the required BAR and a prescribed chord length at the hub.

Typically, about 100 geometries are generated within a generation, after which each geometry is subjected to a series of three PROCAL computations:

1. Steady computation of open water characteristics
2. Unsteady computation in the specified wake field, iterated to the specified design point using the inflow speed as iteration variable.
3. Cavitation computation for the same condition as the unsteady computation.

Propeller computations were done with PROCAL, a boundary element method (BEM) which computes the inviscid flow around the propeller within the ship’s wake field. Besides efficiency, the calculations give the pressure distribution and the extent and dynamics of the sheet cavitation developing on the propeller blades. PROCAL has been developed by MARIN within the Cooperative Research Ships (CRS) framework and has been extensively validated.

The results of the PROCAL computations are evaluated and converted into objectives and constraints. Besides maximizing the behind efficiency of the propeller in the wakefield, also the hindrance from cavitation is to be minimized. In the exploration phase (not reported in this paper) it was found that minimizing both the hull excitation and the cavitation volume provides diversity on the generations while converging towards contemporary propeller designs. Hence, three objectives are defined as given in Table 2. Further, in addition to the objectives, three constraints are used to avoid cavitation erosion in the prescribed design condition.

Table 2: Objectives and constraints within the propeller optimization

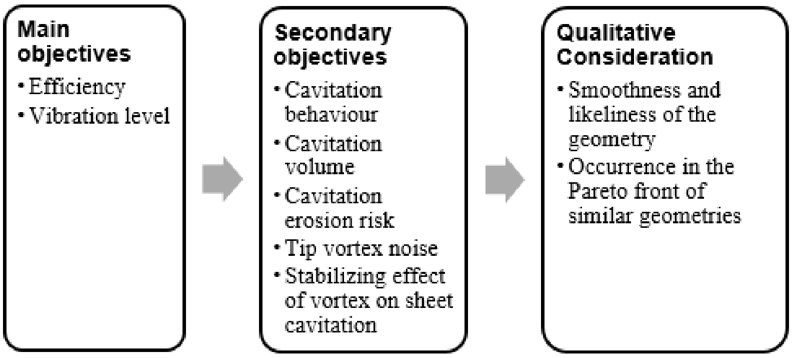
Objectives	**Constraints**
1. Maximize behind efficiency	1. Avoid bubble cavitation with at least 5% margin on cavitation number σ_N
2. Minimize hull excitation as measured as a virtual force on a flat plate above the propeller	2. Comply to the cavity-planform criterion for suction-side sheet-cavitation. The closure line of the sheet cavity is to be sufficiently directed upwards such that the sheet cavitation merges smoothly with tip vortex cavitation.
3. Minimize cavitation volume on all blades	3. Comply to the time ratio and aspect ratio criteria for pressure-side cavitation as determined in the EU EROCAV project.

The optimization algorithm converges to the Pareto Fronts in which the objectives are optimized within the given design freedom, while complying to the constraints.

Such optimization was performed for a subset of 64 propellers within the F-series matrix of 150 propellers. Rather than examining each optimization in detail, the F-series design process focused on achieving similar performance for the F-series propeller compared to the optimized propellers.

For the design and smoothing towards the geometry of the F-series, the best propeller is selected was hand selected from each individual optimization. Each time selection criteria as presented by Table 3 were considered to choose the surviving individual to be used as input for the smoothing process to create the F-series.

Table 3: Selection process to select the F-series survivor from each particular optimization



In the selection process first the main objectives were considered, but also secondary objectives and qualitative considerations were used. The selected geometries were processed and smoothed, followed by analysis of all 150 propellers according to the design input.

3.6 Geometry and Smoothing

Each radial distribution was described using a Bézier curve of which the control points follow from polynomials as function of the main parameters PD, BAR and Z. The following summarizes the conclusions during the iterative path towards the geometry description of the F-series:

- The radial thickness distribution of the F-series follows from the DNVGL rules. The final polynomial description captures the main trends from the rules. For simplicity reasons, it was chosen to describe the thickness with a simple cubic Bezier curve, such that both the thickness at 0.6R and 0.8R comply. The thickness at the tip is equal (0.0035D) for all propellers.
- A fit was made on the input parameters of the outline function of the selected propellers from the optimizations. It was found that the chord distribution was captured by a 4th order Bezier with control points at the hub, 0.8R and the tip. The control points are first estimated by a function f(BAR,Z) after which the control point at 0.8R is used for fine-tuning towards the exact BAR with a complex-step derivative method. The majority of the propellers is relatively well captured by this simple and smooth description of the chord length.
- For the skew a similar procedure was followed. A cubic Bezier curve with quadratic polynomial input captures the majority of the propellers sufficiently accurate and provides consistency within the F-series. The 3-bladed propellers feature higher skew and more variation in skew compared to the 7-bladed propellers due to the optimization for the lowest hull excitation levels. In general, the wider blades (higher BAR or lower Z) have higher skew.
- The rake of the F-series balances the skew-induced rake and keeps the blade as tight as possible above the hub. The rake was not optimized for hydrodynamic performance. No special tip-rake was applied. The rake was prescribed in the polar description, being independent from skew and pitch.
- The pitch was designed using propeller optimization studies for the subset of 64 propellers. The design space was already fixed in skew and chord for simplicity. Initial optimizations allowed much freedom with a 5th order Bezier curve. It was found that also a simple cubic Bezier curve, always forced towards maximum pitch at 0.7R, would describe the optimization results sufficiently accurate. Finally, only the pitch reduction at hub and tip are required. Bilinear polynomials were found to capture the trends from the optimizations. The low BAR propellers have more pitch reduction, compared to higher BAR propellers, both at the hub and at the tip. According to the optimizations, a pitch distribution like the F-series provides an optimum balance between efficiency, hull excitation and the stability and non-erosiveness of the sheet cavitation.
- Pitch and camber were balanced iteratively to obtain smooth distribution for both while maintaining acceptable cavitation behaviour. The radial camber distribution was described using a cubic Bezier curve. The input are quadratic polynomials for the camber at the hub, the camber at 0.7R and the camber at the tip. The optimization steers towards relatively high camber at the root for the low PD and low BAR propellers, which appears to be optimal for the behind efficiency if there are low velocities in the wake near the hub. The camber at 0.7R is mainly driven by cavitation constraints, either by the bubble cavitation criterion, the cavity planform or the pressure-side cavitation. After smoothing, clear trends were found. The camber at 0.7R increases with PD and decreases with BAR and Z.

4 COMPUTATIONAL PERFORMANCE

The performance of the 150 F-series that are envisioned for production was computed by PROCAL. In this paper, these computational results for the 3, 5 and 7 bladed propellers are presented.

4.1 Efficiency

According to PROCAL, the behind efficiency of the F-series will be higher than the (numerical) B-series as shown by Figure 2. The same conditions were computed, the pitch of the B-series was iterated to similar thrust loading.

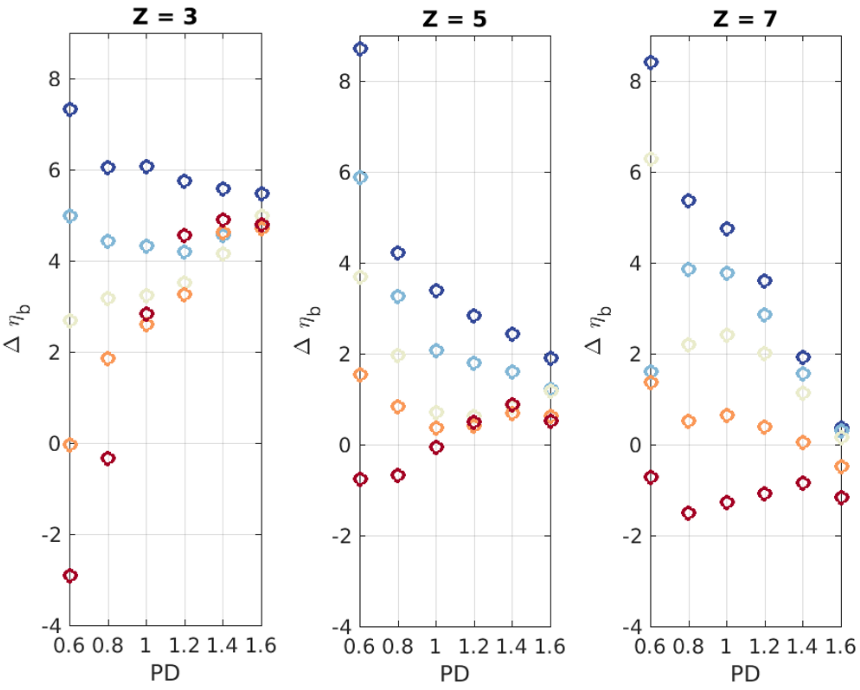


Figure 2: Comparison of F-series computed behind efficiency compared with the (numerical) B-series. From blue, via green, to red: low BAR to high BAR.

It was found that the difference in efficiency between the B-series and the F-series is both due to the higher efficiency in open water, and because of the greater difference between the efficiency in open water and the efficiency in the wake field. This means that the F-series is generally better adapted to the wake field and gives a higher efficiency in open water.

For the 5-bladed F-series the computed open water characteristics (full scale) are presented in Figure 3. The curved black line in the figure for CT represents the ideal efficiency. In addition to the lines for K_T, K_Q and η_0, the cross markers indicate the K_T or CT and η_b in the wake field and the bold lines give an indication of the variation of K_T or C_T and η_b of one propeller blade within the wake field.

The PROCAL computations show clear and consistent trends as function of the blade number and blade area ratio.

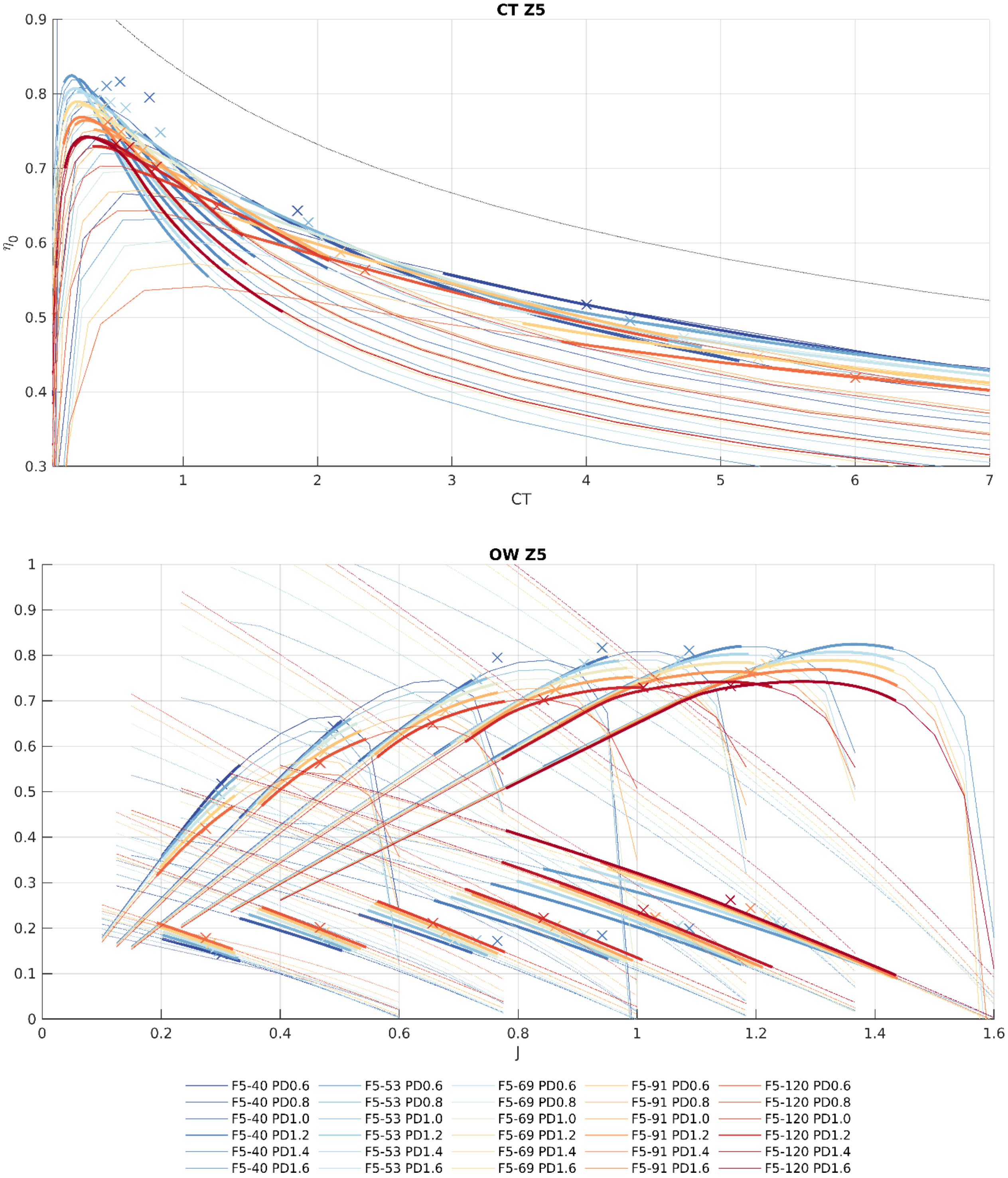


Figure 3: Computed (full scale values) Open Water Characteristics of the 5-bladed F-series

During the design phase, various checks were carried out, including model tests on preliminary F-series designs. Both the model test data and the data corrected towards full-scale performance with commonly applied scale effect from ITTC and the PROCAL computations are presented in Figure 4 for a preliminary F-series design of the 5 bladed propeller with BAR = 0.53 and PD = 1.0.

The efficiency level seems at contemporary value and PROCAL is about correct concerning efficiency close to the design point (J = 0.75) compared to the scale effect corrected results. PROCAL gives some overestimation of KT, but more remarkable is that PROCAL misses the curvature in the KQ at lower J values and high CT values. A significant over prediction on KQ is provided by PROCAL in the lower J-range. Nonetheless, a similar comparison between PROCAL and model tests is observed as for most propellers in the MARIN database. This indicates that there is still a need for model tested open water characteristics.

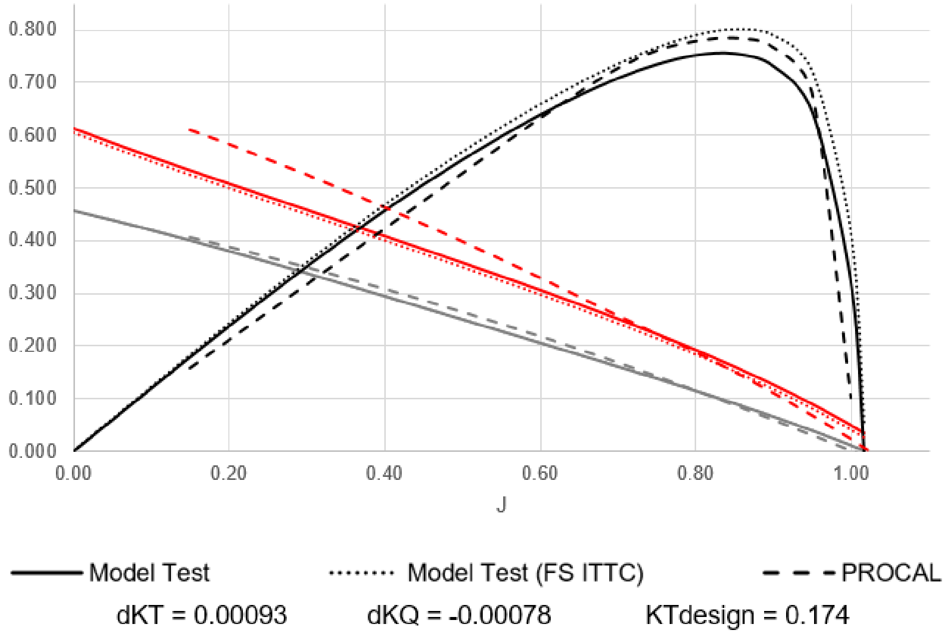


Figure 4: Comparison of model test and PROCAL

4.2 Cavitation

The maximum cavitation area in percentage of the blade area of one blade is presented by Figure 5. In the wake peak, typically 20 to 40 percent of the blade is covered with cavitation. Nonetheless, some of the high BAR propellers with high PD are covered for more than 60% of the blade with cavitation.

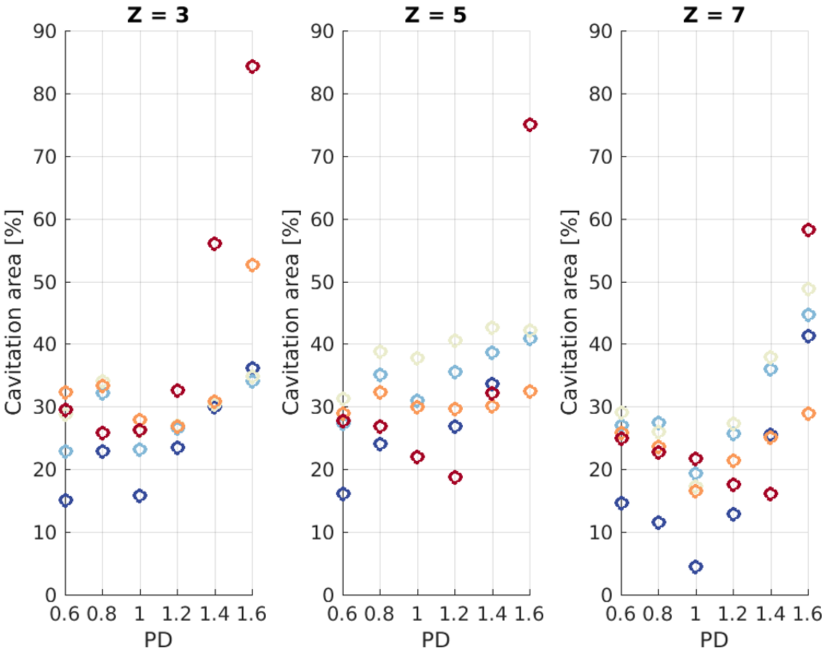


Figure 5: Cavitation area (including area of the super cavitation if any) in percentage of the blade area of one blade. From blue, via green, to red: low BAR to high BAR.

No clear trends are visible for the main parameters although the 7-bladed propellers clearly have less cavitation, and the highest PD propellers have most cavitation. The trends are difficult to explain due to the difference in operating conditions and wakefield. For instance, the ULCV wake (Z=5, PD = 1) causes more cavitation compared to the submarine wake (Z = 7, PD = 1).

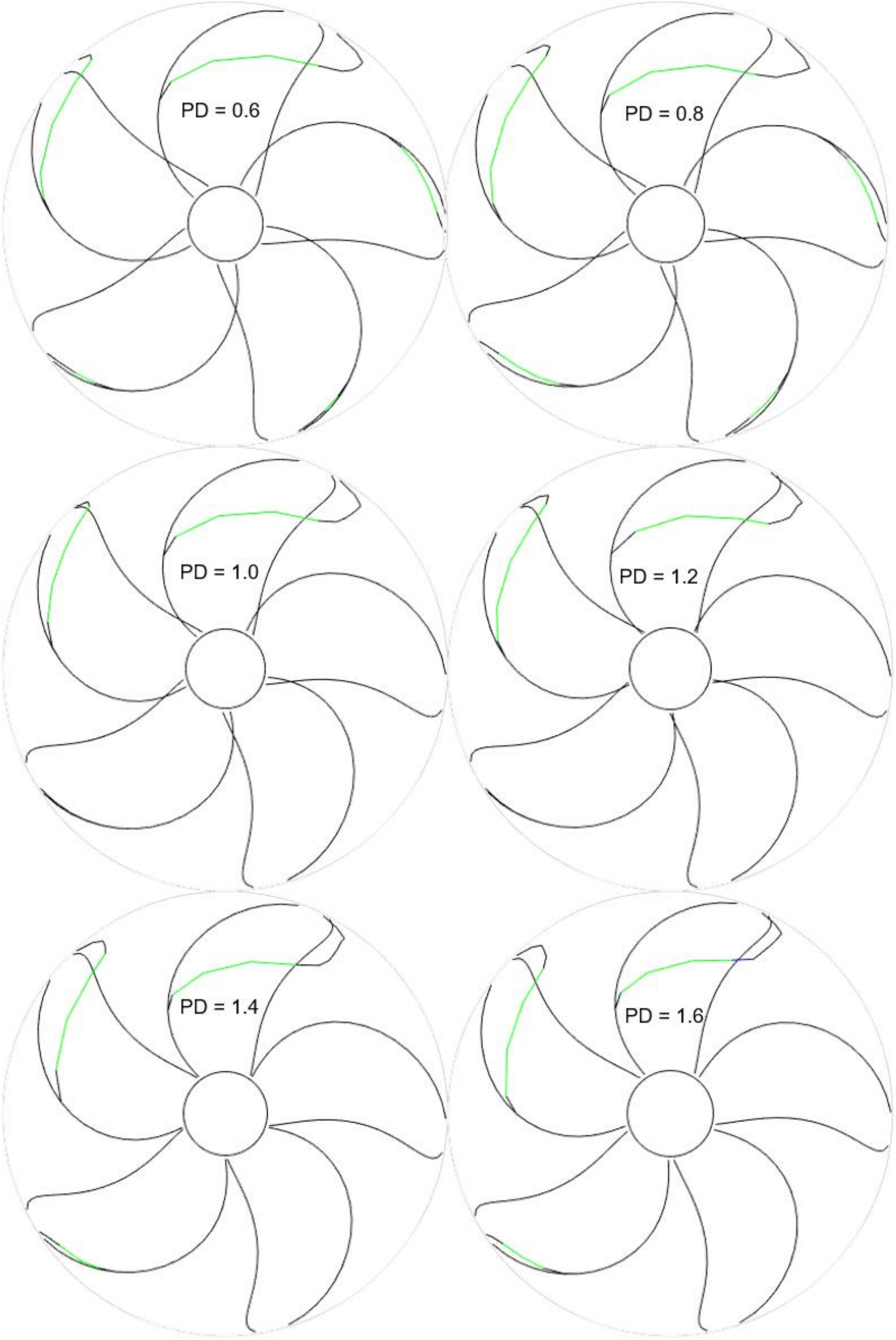


Figure 6: Cavitation sketch of the F5-69

Sketches of the computed cavitation for some of the propellers are presented in Figure 6 for the F5-69 and in Figure 7 for some other propellers within the series. The outline of the propeller blade is presented in black. The outline of the cavitation is presented in different colours according to Table 4.

Table 4: Legend for the colours in the cavitation sketches

Black	Blue	Green	Red	Purple
Non-erosive region	Growing phase, non-erosive	Complies to outline criterion, non-erosive	Erosion risk	Pressure-side cavitation

According to the computations, the sheet-cavitation for most propellers in the F-series behaves exemplary. The cavitation is stable, increasing in length with radii and retracts towards the tip, smoothly ending in the tip vortex. The cavitation behaves in similar consistent manner as shown by Figure 6. However, there are some outliers at the high PD, high BAR, high Z that have some potentially erosive root cavitation at both suction side and pressure side, as shown in Figure 7 for the F7-130 PD = 1.6.

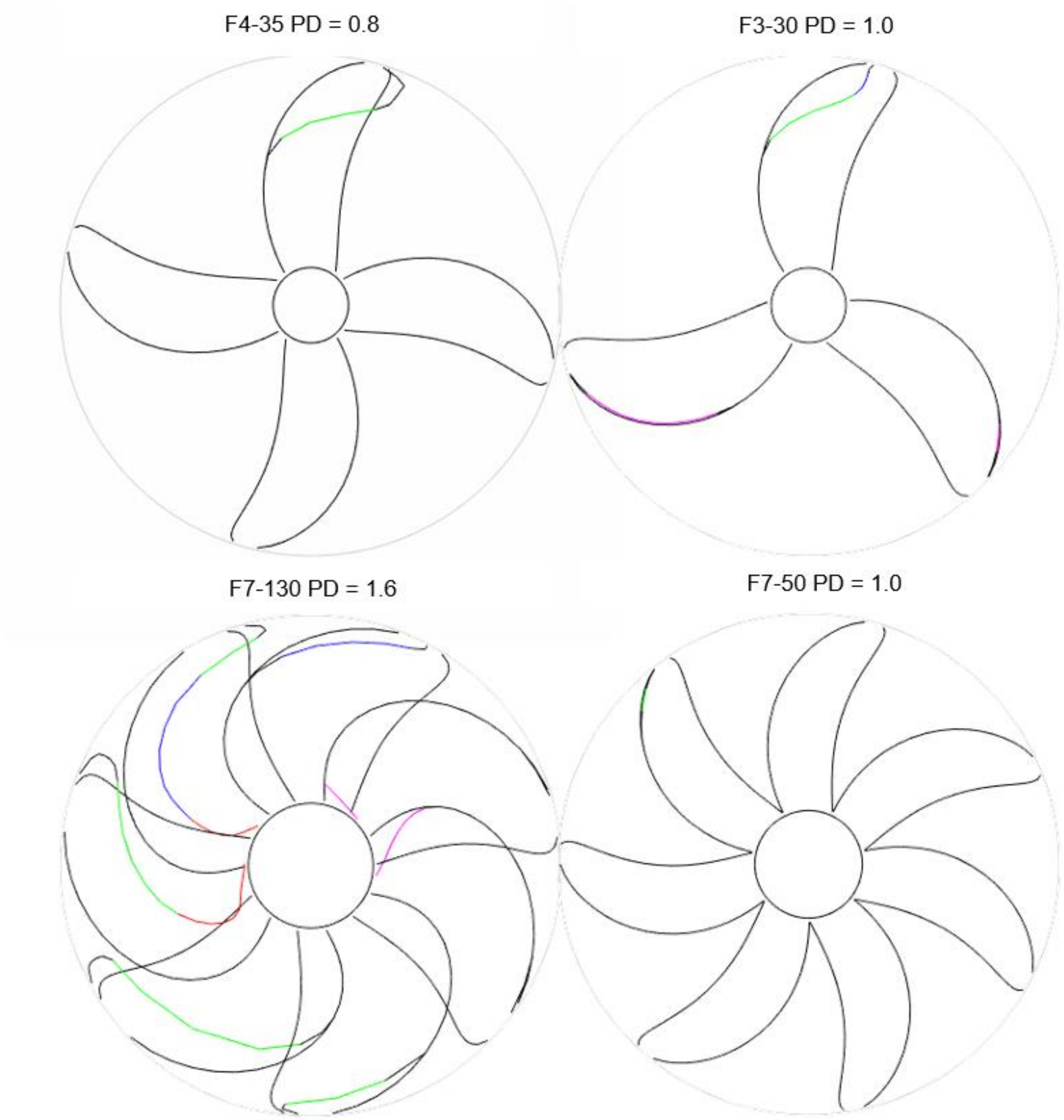
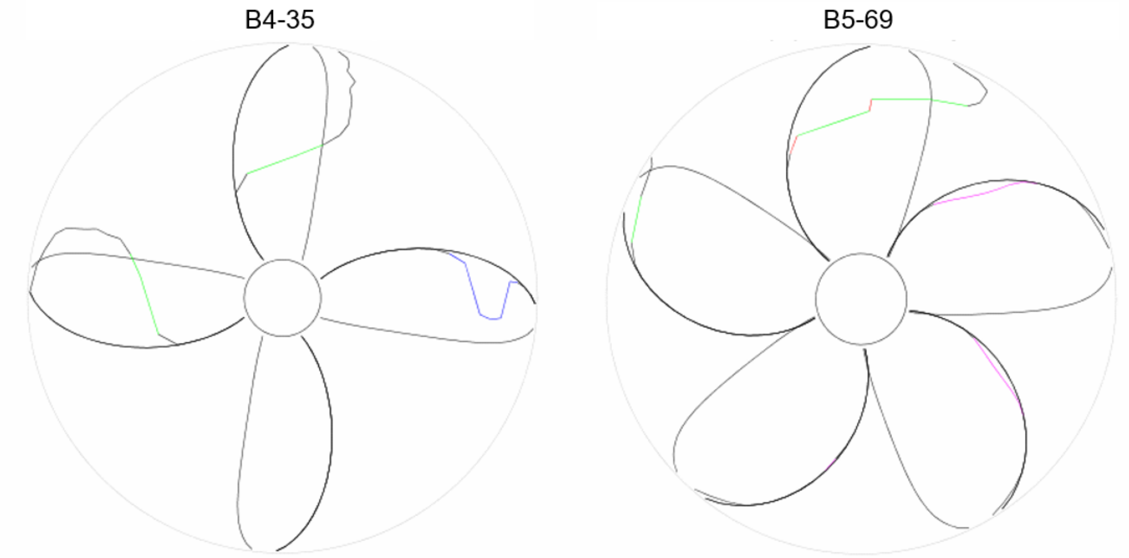


Figure 7: Cavitation sketches of some other propellers

No clear difference in cavitation behaviour as function of blade number was seen, when compared for equal area of one blade, although more super cavitation is observed for the propellers with more blades. The low PD propellers feature cavitation in the top part of the rotation, while the high PD propellers have more cavitation on the down going blade.

For reference, Figure 8 shows an example of the comparison between the cavitation behaviour of the B-series and the F-series. Compared to B-series the cavitation behaviour of the F-series at similar condition is much closer to contemporary designs. In general, the B-series feature less stable sheet cavitation, for the lower BAR propellers bubble cavitation is often observed, while pressure-side cavitation often takes erosive shapes.

Due to the focus on high efficiency, the cavitation volume of the F-series is not always less compared to the B-series, but the behaviour is favourable. For higher BAR, the differences between the behaviour of the B-series and F-series become smaller.



B4-35

PD similar to F4-35 PD = 0.8
Bubble cavitation
Unstable sheet cavitation

B5-69

PD similar to F5-69 PD = 1.0
Erosive pressure-side cavitation
Unstable sheet cavitation

Figure 8: B-series propellers computed in similar conditions as the F-series

4.3 Hull Excitation

Traditionally, hull excitation was quantified by the maximum first harmonic amplitude of the pressure fluctuation. Typically, 3 to 5 kPa was regarded as a limit for merchant ships, measured above the propeller. The levels for the F-series are shown in Figure 9 (left) which are determined by searching the maximum amplitude on a virtual plane above the propeller. A tuning coefficient was used to represent the V-shape of most aft ships.

Significantly high levels are computed compared to traditional experience with model tests, especially for the higher pitch propellers. Note that for both cavitation volume and hull excitation (especially the peak of the first harmonic) PROCAL is known to be conservative, presumably due to the absence of prediction of the rolling motion of the sheet cavitation along the leading edge towards the retraction into the tip vortex.

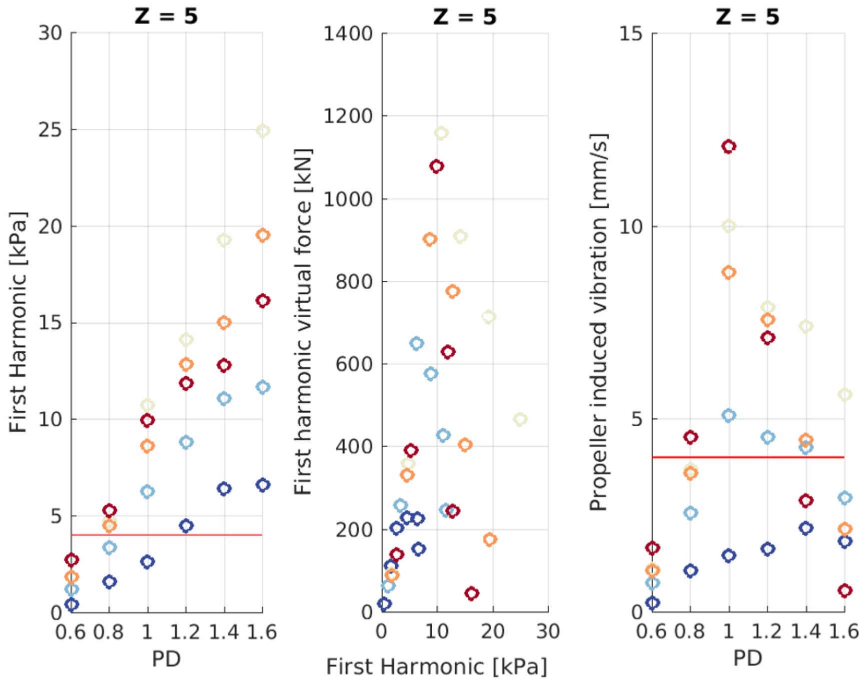


Figure 9: Computed hull excitation for 5-bladed F-series propellers. From blue, via green, to red: low BAR to high BAR.

However, for qualification purposes, the magnitude of the excitation force is preferable to the hull pressure fluctuation level at one point only. To support of this statement, Figure 9 (middle) considers the relation between the maximum pressure fluctuation and the integrated force. It shows that the correlation between the integrated force and the maximum pressure pulse is quite poor. Therefore, during the design of the F-series, the integrated force was used as an quantification of the hull excitation.

For the interpretation of the hull forces, an empirical approach as proposed by DNVGL was used that relates the first harmonic virtual force to vibrations levels. Figure 9 (right) presents the vibration levels of which up to 4 and 10 mm/s is classified as average for ships with aft and midship or forward accommodation respectively.

Although both the computations with PROCAL and the DNVGL approach are engineering tools, they were considered powerful to steer the characteristics of the F-series propellers. This analysis shows that the F Series are designed with a focus on high efficiency, while generally staying within the average comfort zones.

The approach by DNVGL only uses the first harmonic contribution to the excitation force due to the substantial uncertainties in the measurement or computational methods for the higher harmonics. Therefore, the higher harmonics are correlated within the empiricism of the approach. Nevertheless, during the optimization, the choice was made to minimize the total virtual force, instead of just the first harmonic force. Most likely, the optimizer would abuse energy exchange from the first harmonic to the higher harmonics.

5 CONCLUSIONS

The F-series was designed for high efficiency with acceptable cavitation behaviour and hull excitation, approaching the performance of modern industry standard propeller designs. The following conclusions were drawn:

- The F-series was defined in main parameters blade number Z from 3 to 7 blades, pitch (PD) ranging from 0.6 to 1.6 in steps of 0.2, each with five variants for the expanded blade area ratio BAR. Relatively more focus was put on propellers with lower BAR.
- Contrary to the B-series, the radial distributions of the F-series propeller designs vary systematically and smoothly in geometry, tailored to its most common ship type. For each of the 150 F-series propellers a design condition was defined as basis for the computational evaluation.
- As a design philosophy, the aim was to have a smooth input in order to achieve a smooth output as well. The input was prescribed for each combination of PD, BAR and Z. The data was based on the analysis of typical ships, after which it was smoothed and interpolated during the iterative process in the design optimization cycle.
- Optimization studies were performed for a subset of 64 propellers within the F-series matrix. Efficiency was maximized, while hull excitation and cavitation volume were minimized. Cavitation erosion constraints were used to steer towards non-erosive cavitation.
- The design of the F-series was approached as an iterative process between the supplied design input, the description and freedom of the design variables and the optimization results. In each design iteration the best geometries from the optimizations were selected and smoothed over the main parameters PD, BAR and Z. Subsequently, the input is further adjusted towards better convergence and smoother description of the F-series geometry.
- Several iterations of decreasing complexity and increasing smoothness were done to arrive at contemporary designs for each of the F-series propellers. The radial distributions were simplified and described using Bezier curves with polynomial input as function of the three main parameters.
- According to the PROCAL computations the behind efficiency of the F-series will be higher compared to the numerical B-series. In general, the F-series are both better adapted to the wake field and provide higher open water efficiency.
- The sheet-cavitation for most propellers behaves exemplary in a stable manner and is consistent over most of the propellers within the series. Typically, 20 to 40 percent of the blade is covered with cavitation.
- For qualification purposes the magnitude of the excitation force was preferred over the traditional hull pressure fluctuation level. For the interpretation of the hull forces, an empirical approach from DNVGL was used which relates the first harmonic virtual force to vibrations levels.
- The F-series geometry was designed for high efficiency and average comfort levels thereby allowing significant amount of non-erosive cavitation. Compared to the numerical B-series, the performance of the F-series is better both in efficiency, cavitation behaviour and hull excitation.

In summary, the F-series will provide realistic and competitive efficiency levels balanced against common cavitation, noise and vibration requirements. Over time, the F-series is intended to replace the B-series.

The coming two years, all propellers will be manufactured and tested. All results will be shared with the participating organisations in this JIP. Furthermore, the data will be implemented in software for practical use by the participants.

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