Parameter Influence Analysis in Propeller Optimisation

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ABSTRACT

This paper presents an optimisation of propeller blade geometry while the propeller is evaluated for different operating conditions. Sheet cavitation is considered by selective constraints in the condition of a fixed wake. The automated optimisation is performed on a propeller for a contemporary cruise vessel with high demand for a certain efficiency and pressure pulse limit; the starting point is an already manually optimised propeller. The defined geometric parameters are used to manipulate the original design by the applied genetic algorithm. These parameters are investigated in a sensitivity analysis to evaluate each impact on the objectives and constraints. Subsequently a second optimisation was accomplished focusing on the input parameters with the essential impacts.

KEYWORDS

Multi-objective optimisation, sensitivity analysis, vortex lattice method, cavitation prediction, constrained propeller design

1 INTRODUCTION

Global market development, increasing environmental concerns and incessant rising fuel prices demand for high-grade efficient propulsion systems. This puts high pressure on the propeller designer to develop well-engineered and customized propeller design in a short timeframe. Each conceptual design is always unique and requires individual consideration on several constraints. The propellers are required to be designed at the limit to provide maximum efficiency. Tuning the propeller geometry towards efficiency changes its characteristics also regarding the cavitation behaviour, vibration and inboard noise. The only solution is to find a compromised geometry valid only for each specific ship and the specified requirements.

Common practice in propeller design is to develop a preliminary design concept and improve this by finding the best compromise between the objectives and constraints, thus naturally an optimisation task. Cavitation is in this procedure an omnipresent constraint. It influences the typical objectives, namely propeller efficiency and propeller induced pressure pulses, directly in first order. The process of cavitation development, expansion and decomposition is physically profoundly complex and still yet not even fully understood. Thus to obtain information on the cavitation behaviour of the propeller, experimental results or highly unsteady and computationally costly calculations are required. However, the only option to deal with this problem during the design process, within an appropriate time frame, is to apply less accurate but faster potential methods. These methods cannot resolve detailed flow phenomena but they provide fairly accurate performance predictions (e.g. Lu et al. (2012)) and, with elaborated constraints, have shown to be sophisticated enough to perform optimisation design tasks.

In cases like in optimisation tasks, when the number of variables raises the complexity of a system, methods for sensitivity analysis (SA) can help to ascertain the impact of a single input to the system. Thus for the automated optimisation of a system as complex as a propeller, knowledge about the interplay of geometry changes and understanding the system behaviour helps to select only significant variables and thereby reduce the exploration process in optimisation.

In section 2 we describe the selected test case characteristics followed by section 3 introducing the chosen optimisation methodology and the applied numerical tools briefly. Section 4 explains the SA and presents their results and in section 5 we compare the results of two optimisation approaches.

2 STUDY CASE

The demands on the propeller design to fulfil customer requirements regarding efficiency and performance are always high. Occasionally the restrictions on the efficiency and propeller induced pressure pulses are particularly strict. The test case setup provided thus an exceptional basis for an interesting survey of the capabilities in automated optimisation.

The case study was based on a propeller design for a novel cruise vessel with especially high demands for propulsion efficiency and low pressure pulse levels and cavitation induced noise. The design needed special attention in order to satisfy the high demands. Thus careful manual design iterations where made and the efficiency and pressure pulse level were optimised, following the classification rules as well as internal strength requirements at the same time. Also considered in the manual design were other aspects like noise from tip vortex, performance in off design condition, manufacturability, risk for cavitation erosion etc.

The propeller design is commonly adjusted to fit the resistance for the vessel, measured wake field and maximum shaft power. Parameters like propeller diameter, number of blades and shaft rpm are optimised in an early stage in order to fix the order scope. These parameters are therefore not considered in neither of the optimisation studies but may be included for other case studies.

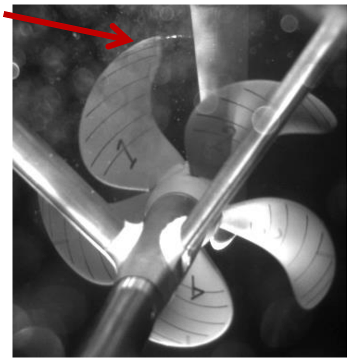


Figure 1 Model test of the propeller under consideration in depressurised towing tank

Model tests were performed with the designed propeller indicating particularly good results. Both efficiency and pressure pulse level were better than predicted. The sheet cavitation was noticeably less than predicted and the reason is not yet fully recognized. Figure 1 shows the model propeller operating in the wake field. A small amount of sheet cavitation can be seen close to tip, developing into some tip vortex cavitation. The blade position of maximal sheet cavitation is fairly close to the prediction.

3 OPTIMISATION METHODOLOGY

There have been several different approaches in propeller design within the recent three decades. Burnside et al. (1979) presented, as one of the first, propeller design recommendations with special considerations regarding propeller induced vibrations. They considered both analytical and experimental techniques and stated that cavitation has a significant influence on the hull pressure. More recently Mishima (1996) presented the optimisation of propeller blade geometry with respect to sheet cavitation predicted by a vortex lattice method (VLM). The optimisation task was to minimise the torque which was approximated by: first a linear and finally a quadratic function whose coefficients were determined by the numerical propeller analysis program. Thus the actual optimisation could be accomplished by a classical optimisation method of Lagrange multipliers. Han (2005) presented an optimisation of the propeller blade geometry in a fixed effective wake distribution. Han's work showed considerable improvements in cavitation performance when applying cavity volume and area constraints.

Table 1 Optimisation constraints and formulations

Item	Name	Formulation
Maximum cavity Volume	cavVol	$\frac{Vol}{R^3}$
Maximum cavity volume change	cavVolChange	$\left.\frac{Vol}{R^3}_i\right/\frac{Vol}{R^3}_{i-1}$
Sheet thickness at the tip of key-blade	Tip1, Tip2, Tip3	$\frac{cavArea}{cavLength}$
Maximum chord-wise centroid	cavCentriod	$\frac{\sum_{i=1}^{N_{panel}} t_i}{N_{panel}}$
Thrust coefficient	K_T	$\frac{T}{\frac{1}{2}\rho n^2 D^4}$

Vesting et al. (2011b) proposed the adopted constraints on sheet cavitation to tolerate or constrain selective types of cavities. These constraints were further developed (Vesting et al. 2011a) and are still under investigation.

The constraints considered in this work are given in Table 1. In general we define the blade position with the maximum non-dimensional cavity volume, predicted from the VLM, as the 'key-blade-position' and assume that cavities at this position and in vicinity have the largest impact on the pressure pulses. Hence, the blade positions around the key-blade-position are evaluated regarding the constraints as well.

As it is discussed in Vesting et al. (2011a) and Vesting et al. (2011b), the constraints are essentially selected to control cavity formations that either could lead to erosive cavities or affect the pressure pulses explicitly. This can be done for instance by avoiding development of travelling cavities from sheet cavity by monitoring the cavity closure line or by avoiding mid chord cavitation by constraining centroid of the cavity. Monitoring and constraining the cavity thickness at the blade tip showed so far a significant impact on the pressure pulses and might restrict the likelihood of developing a cavitating tip vortex.

When including the modification of the blade thickness, as described in the following section, the risk raises that the stress inside the blade would become too high. Thus we included one more constraint: Each design is evaluated with the classification notes 41.5 for 'Calculation of Marine Propellers' according to Det Norske Veritas (DNV). The created design is supposed to fulfil the high cycle stress criterion for dynamic stress amplitudes in the propeller blade as well as the low cycle stress criterion. A thin tip thickness will increase risk for propeller song when von Kármán vortices coincide with propeller blade natural frequencies, causing resonance that are clearly audible on board ship. This is an important design criterion on passenger vessels but will not be considered during the automated optimisation.

Table 2 Optimisation parameter as control points of the shift function and their range of influence

Parameter curve	0.2 r/R 1.0		
Pitch	X3	X5	
Camber	X2	X3	
Skew	X2	X5	
Chord	X2	X3	X4
Thickness	ThTip		
Rake	rakeTip		

3.1 Geometry Variation

In optimisation tasks the number of free variables is one of the crucial elements and decides over success and failure of the optimisation algorithm. The convergence of any optimisation algorithm depends strongly on the number of free variables and rises disproportionately (Harries 2003). Hence a design task to be optimised requires a sophisticated, problem dependent description with the least number of descriptors as possible. In our view, the natural choice is parametric modelling.

The concept of parametric modelling relies on the possibility to capture the essence of the design in a small number of variables and thereby reducing the design space. Variables in that sense are of a higher order than conventional coordinates of certain geometry. They may be computed through formulas and might be in relation to any other geometry and are referred to as parameters.

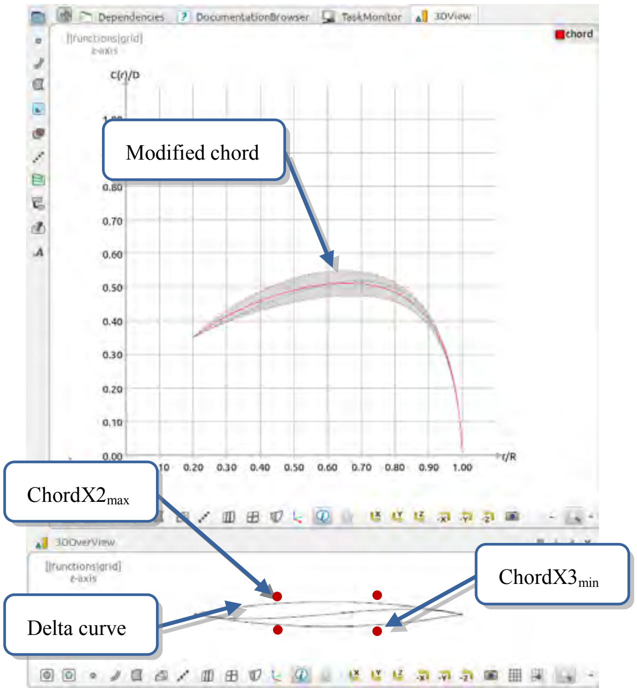


Figure 2 Parameter shift in FRIENDSHIP-Framework on an original chord parameter distribution curve (upper frame). B-Spline shift curve with control points (lower frame)

In case of a marine propeller a common modelling approach is the use of parameter distribution curves for instance for the chord length as a function of the radius. Figure 2 shows a typical parameter curve $C(R)$ providing the local value of chord length by the ordinate value. The profile length varies then with the position in radial direction. Following the parameter curve, the blade starts with a hub radius, has its maximum length between *60%* and *70%* of the radius and ends with zero chord at the blade tip.

In addition to this parametric approach, and to be able to manipulate an existing parameter distribution curve and to further reduce the input parameter to an optimisation, we applied a shift function controlled by a B-Spline curve with less control points than the parameter curve. In this concept the function value of the shift function is applied to the original parameter curve. In case of the example in Figure 2, the grey area highlights the range in which the curve can take any form according to the delta value supplied from the shift function. Here the shift function has two control points that can be changed independently and whose ordinate value is used as the input parameter to the optimisation. The applied control points for each of the changed parameter curves are summarised in Table 2.

4 SENSITIVITY ANALYSIS

A global SA allows studying the dependency of a given model (e.g. numerical) and its input factors. Possible ways to do this is to use standardized regression coefficients (SRC) in a multiple regression analysis or ranked data in a standardised rank regression coefficients (SRRC) analysis. However the drawback of these methods is that they are associated to the model fit (Saltelli et al. 1998). A method independent from a regression fit was developed in the 1970s, which allows for the decomposition of a model output. The Fourier amplitude sensitivity test (FAST) is based on Fourier series to represent the output function and was extended to the 'extended FAST' by Saltelli et al. (1999). The extended FAST also include the interaction effect of the input variables on the output variance.

Eventually, the extended FAST method calculates the sensitivity indices by analysis of the model variance. Considering a model $Y = f(X)$ as the output, where X is a vector of n input variables, then the decomposition is obtained using mono-dimensional Fourier transformation of f (Saltelli et al. 1999). The design space is explored along a curve defined by a parametric equation of the transformation functions and a set of different frequencies. Each input X_j oscillates periodically with its corresponding frequency ω_j when systematically changing the curve. The model Y shows deviating periodicities, depending on the influence of the j-th input parameter, e.g. if X_j´s influence is high, then the oscillation of Y at ω_j are of high amplitude. This is the basis for the sensitivity measure, which is described in detail by Saltelli et al. (1999). Finally the total variance is the sum of all conditional variances:

$$V(Y) = \sum_{j=1}^{n} V_j + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} V_{jk} + \cdots + V_{12\ldots n} \qquad (1)$$

where V_j is the variance of the output related to the input variable X_j. This called the first-order-effect. Accordingly represent V_{jk} the second-order-effect from the interaction of input variables X_j and X_k and so forth. The total sensitivity index (S_{Tj}) is eventually computed as the sum of the first and higher order effects divided by the unconditional output variance.

$$S_{Tj} = \frac{V_j + V_{jk} + \cdots + V_{12} \ldots n}{V(Y)} \qquad (2)$$

The method as outlined is implemented in the ‘SimLab’ software for SA (Giglioli 2008) and was applied in this study. We consider the numerical results for the propeller as the model to predict the response of our objectives and constraints. Of particular interest were the propeller efficiency and the propeller induced pressure pulses on the hull. However, also the influences on the cavitation constraints were of interest.

The SA was performed with *2035* input variants of the propeller, created, according to SimLab, in uniform distribution for each input parameter within its selected limits. The least number of input variants according to Simlab are 65 variants per factor for the selected method. However, we selected 2^k variants to compute, were k is the number of input factors, which is according to Myers et al. (2009), the suggested number of designs to perform a simple one-dimensional response surface. With a response surface the numerical effort is negligible and the number of variants is unlimited. Thus the same set of variants could be used to create response surfaces for each output and perform the SA with a larger number of variants which should lead to a supporting result of the parameter contributions.

A difference between the FAST and extended FAST method was notable but rather small. The FAST method exclusively based on calculated results, show differences for the cavity constraints which would be influenced only by a few parameters. The extended Fast however, shown in Figure 3, based on the same input variants, finds some interaction effects. The results reveal a dominating influence of the camber X2 parameter on all objectives. The cavity volume and thereby the change in cavity volume depending on the blade position, is almost exclusively influenced by the maximum camber as well. Camber distributes the low pressure region over a wider range on the blade (compared e.g. with the pitch parameter), hence small changes in camber have higher impact on larger cavity volume changes.

The second camber parameter follows this trend in alleviated manner. Surprisingly, the skew variation at the tip has a significant influence on the efficiency but rather small on the pressure pulses according to the SA. The remaining parameters have only an insignificant impact on the objectives.

This is different for the cavity constraints. For the cavity thickness at the blade tip region one can see a dominating dependency on the thickness parameter and the pitch change at the tip. Both are complementary factors for the cavitation created at the leading edge; if the blade profile is thin, it will have a positive effect on the pressure pulses and the efficiency, but the blade section becomes very sensitive to the angle of attack regarding cavitation at the leading edge. This is however depending on the case since the angle of attack is directly coupled to the variation in wake during one revolution. On the other hand a suitable combination would lead to less cavitation.

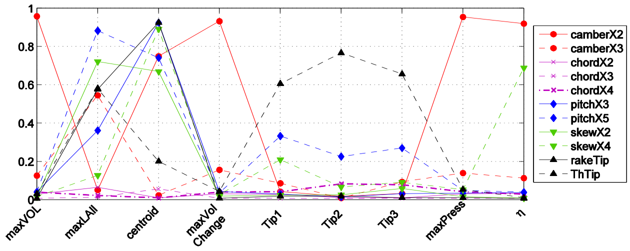


Figure 3 Parameter influence on constraints and objectives based on calculated results

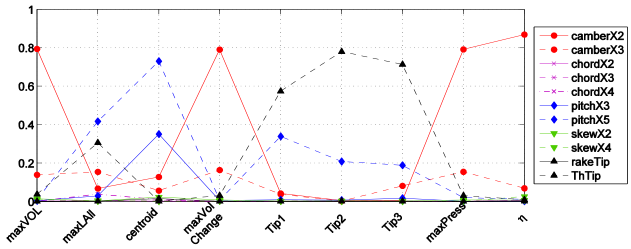


Figure 4 Parameter influence on constraints and objectives based on RSM estimation

The influence on the cavity constraints for maximal length and the centroid is not explicitly resolved. The SA certifies a high influence for almost all parameters on these two constraints. Only the chord length parameter has a small impact on them. The first-order influence of the SA with computed results (not shown here) draws a much clearer picture, where it is only the pitch and the thickness that influences the cavity length and the blade tip thickness and camber parameter that affects the cavity centroid. The unclear interaction effect for the centroid can possibly be explained with very small variation of the centroid among the calculated results. Calculating the coefficient of variation among the computed variants reveals that this is only 0.055. For the cavity length however, there was no considerable difference in variation compared to the other model outputs.

A second SA was performed based on results estimated by a response surface. In this case the evaluation of one propeller variant is done within a few seconds. The applied method, the Kriging approach, is based on the assumption that an unknown value can be estimated by the weighted sum of some given samples at various locations. We utilized the DACE toolbox (Lophaven et al. 2002) for Matlab for the Kriging constructor which follows the method presented by Sacks et al. (1989).

The result of the second SA is summarized in Figure 4. This analysis was realized with a set of *9955* propeller variants estimated from the response surface. As for the SA with the computed results, the input parameters are uniformly distributed between the limits for each parameter. The results show a more distinct resolution of the parameter impact. Although the main impacts obtained from the first analysis are the same (for pitch, camber and blade thickness), the influence from skew and rake disappeared entirely. The unclear influences on the cavity constraints are resolved as well –it is according to this only the pitch and the thickness that have a major influence on the maximal cavity length and the centroid.

5 OPTIMISATION

The automated propeller optimisation with constraints on cavity shape and size was here performed only as an add-on after the conventional design procedure. The conventionally designed propeller represents also the starting point or baseline-design for the optimisation. As outlined in section 2, the design is already manually iterated to meet the required performance. Thus the expected improvement due to the supplementary optimisation is rather small.

The evaluation of a variant is composed of two individual computations: a) the performance of the propeller in open water inflow and b) the propeller performing in the wake of the ship. However, for both inflow situations it holds that the inflow is not affected by the propeller. Hence, the optimisation was restricted to an equality constraint for the thrust with a very small tolerance of ±*1.5%*. The small thrust tolerance is also needed for a fair comparison of the designs among each other, since the thrust load has a considerable influence on pressure pulses and on the efficiency. For a) the condition is to fulfil the propeller efficiency requirement, while b) constitutes the actual working environment of the propeller and forms the condition for the competing objective of reduced pressure pulses induced by the propeller on the ship hull.

Both evaluations are accomplished with potential flow simulations. This methods offer sufficient accuracy to compare the results in relation with each other and a benchmark, in a reasonable short evaluation time. For the propeller performance, including the prediction of sheet cavitation, we utilized the vortex lattice method MPUF-3A (He et al. 2010). In this method the propeller blade geometry is represented by a lattice of discrete vortices distributed on the mean camber surface, which have to be determined from boundary conditions. First development of a numerical method for a lifting surface prediction was presented by Kerwin (1961). The method was further developed by introducing distinct set of source sheets for a blade thickness distribution and to represent sheet cavity thickness (Lee (1979), Kinnas (1985) and Kerwin et al. (1985)). The current version of the applied tool includes among other features, wake alignment, mid-chord cavitation, thickness-load coupling and hub influence.

The pressure pulses are calculated with a boundary elements method to compute the pressure amplitudes of the first three blade harmonic frequencies. 'HullFPP' (Sun et al. 2007) solves the diffraction potential on a flat hull dummy surface, by applying Green´s formula. However, the objective was the maximal amplitude of the first blade frequency which occurred on one of the surface panels.

We applied the setup in two separate optimisations: the first one including all parameters for skew, camber, rake, pitch and chord, in total 11 parameters; and the second one based on the knowledge obtained from the SA. The input parameter could be reduced in the latter case to only 4 input parameters: camberX2 & X3, pitchX5 and skewX4. In both cases a genetic multi-objective optimisation algorithm, the NSGA-II by Deb et al. (2000), was applied.

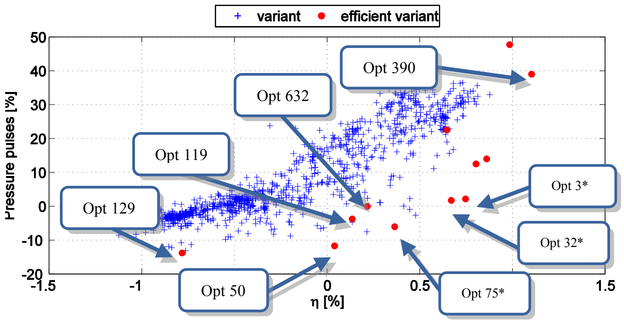


Figure 5 Result of the first optimisation, highlighting the variants of particular interest

In the first optimisation the algorithm created *995* usable variants in *50* generations. However, only *17%* were valid regarding the constraints on the thrust coefficient. Out of these variants the best improvement was obtained with an increase in efficiency of *+0.14%* and a reduction of pressure pulses by *-3.73%* compared with the initial design. Thus the variants created along the Pareto front were reinvestigated by adjusting their blade pitch to compensate the mismatch in thrust. In Figure 5 all variants are plotted relative to the initial design for the first optimisation. The variants of particular interest are highlighted by bullets and the corresponding names. Each of the variants marked with a '*' were re-optimised employing a tangent search algorithm (Hilleary 1966) to minimize the difference between created thrust and target thrust coefficient. The best result achieved for the adjusted variants was then an increase in efficiency by *+0.46%* with a reduction of pressure pulse of only *-0.61%*.

Commonly, an optimisation algorithm is expected to converge quicker with less input parameters. This could exactly be seen from the second optimisation. Figure 6 compares the convergence history of the objectives for both optimisations. Here the objectives are again given relative to the initial design. From the first optimisation one can see that there is a wide variation among the variants while for the *final* optimisation a variation abated already after *150-200* variants. However, as for the first optimisation, the constraint on thrust was once more most restrictive. Only *7%* of the variants were within the allowed range (marked by bullets). In the *final* run, a best variant could be obtained with an improvement of *-4.8%* in pressure pulses and *+0.15%* in efficiency, evaluating almost only half of the variants as in *opt*. The overall trend shows a decline for the converged solutions. This can be seen from the first optimisation as well, even though rather weak.

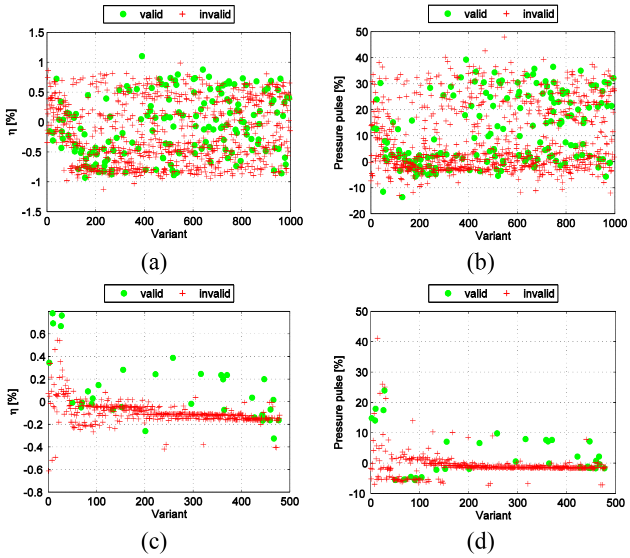


Figure 6 Optimisation history for the objectives. (a) and (b) for the total optimisation, (c) and (d) for the input importance improved optimisation approach

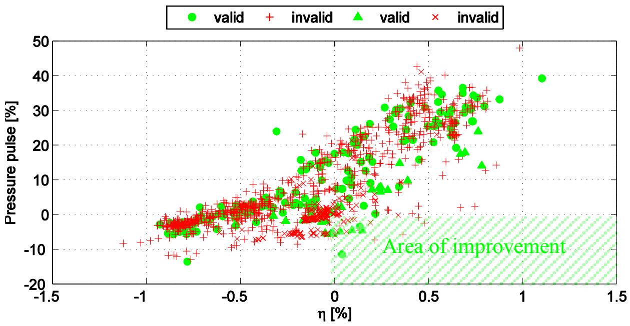


Figure 7 Pareto front of the two optimisation approaches, relative to the initial design.

In Figure 7 the objectives of both optimisation results are plotted with respect to the values of the initial design. Again the validity refers to the equality constraint of K_T. It can be seen from Figure 7 that neither the first nor the final optimisation generated many variants in the area of improved objectives. To be more precise, for *opt* there were exactly two variants and for *final* we could find three variants that were created directly without adjusting the blade pitch. In fact, the adjustment improved only variant *Adjusted 32*, transforming it into the area of improvement. This variant had already a better efficiency but slightly worse pressure pulses than the initial design (compare Figure 5). For variant *Adjusted 75* the adjustment improved the efficiency but deteriorated the pressure pulse from already better to worse by *15%.*

However, Figure 7 provides also a view over the performance of the two optimisation approaches in total. To summarise this: *opt* covered a much wider range of the objectives and created significantly more variants within the range of valid K_T. But still the gathered knowledge of the design problem could not improve the overall convergence of the genetic algorithm.

Variants in *final* on the other hand are much more clustered close to the initial design. Unlike before, the valid variants do not spread over the whole bandwidth but somewhat closer to the Pareto efficient solutions.

The following figures (Figure 8-Figure 11) show the modifications applied to selected variants in relation to the initial design. The selected variants are collected among the valid solutions and along the Pareto front and were already introduced in Figure 5. The solution from the *final* optimisation is included as 'Final opt', which is considered to represent a converged geometry of *final*. Among these variants we find the best in each objective, the most efficient trade-off and further trade-offs according to Table 3.

Table 3 Variants of particular interest; performance in comparison to baseline design

Name	Pressure pulses	η	cavLength	CavVolume	Controid	VolChange
Opt 129	-13,75%	-0,78%	-10,62%	-26,08%	-3,90%	-18,37%
Opt 50	-11,65%	0,04%	-6,19%	-33,64%	-2,96%	-32,44%
Opt 119	-3,73%	0,14%	-8,33%	-3,63%	-4,05%	-2,11%
Opt 632	-0,03%	0,22%	-8,94%	14,85%	-3,98%	14,64%
Opt 390	38,93%	1,10%	-0,08%	81,58%	-1,25%	71,20%
Adjusted 3	0,83%	0,65%	1,83%	6,85%	-0,47%	3,35%
Adjusted 32	-0,61%	0,46%	1,76%	-0,56%	-0,39%	-1,53%
Adjusted 75	7,04%	0,80%	-5,12%	22,85%	-2,10%	24,50%

Figure 8 shows the pitch distribution. Here we can see that most of the variants follow a trend to reduce the pitch at the tip, only the variant with best efficiency shows an increase. Looking at variant *Adjusted 75* it was found that the increase in pitch during the adjustment affected the pressure pulses most among the adjusted variants, from an improvement towards degradation.

For the camber distribution, shown in Figure 9, a geometry trend is somewhat clearer: the better performance regarding pressure pulses with moderate efficiency increase show an increase in camber over the whole radius. While the variants with better efficiency increase and moderate pressure pulse reduction show the trend of a reduced camber. These observations might be in interaction with the changes in pitch. But loosely spoken: In case of focusing on the efficiency, a pitch increase at the tip and a camber reduction seem favourable, while a camber increase and a pitch reduction is better regarding pressure pulses. However, variant *Opt 129* does not follow this statement.

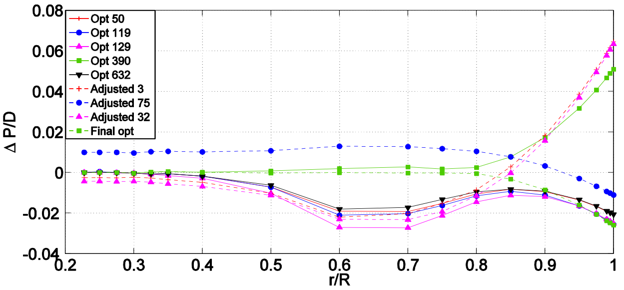


Figure 8 Geometry change in pitch distribution with respect to the baseline design

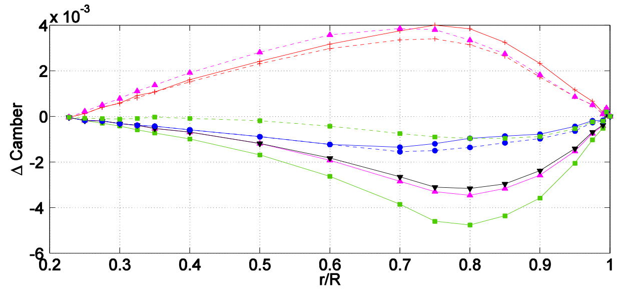


Figure 9 Geometry change in maximum camber distribution with respect to baseline design

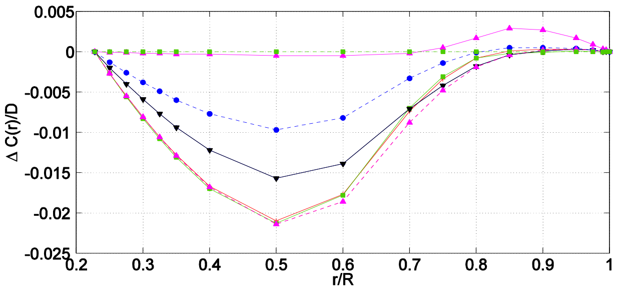


Figure 10 Geometry change in chord over diameter distribution with respect to baseline design

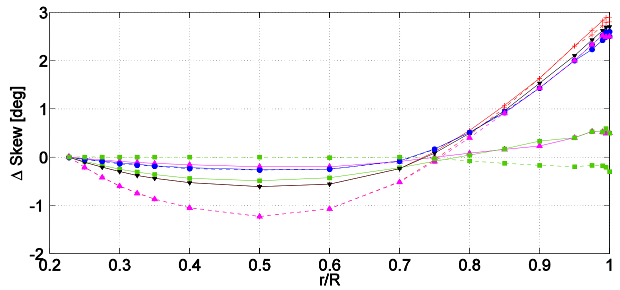


Figure 11 Geometry change in skew distribution with respect to baseline design

A geometry trend can also be seen for the chord distribution (Figure 10). Although we applied three different parameters for the chord curve to change, it was basically only the first one (chordX2) that was changed for the selected variants. The chord length at the tip was not changed except for variant *opt 129*.

The trends for skew are surprisingly not revealing by itself. One can see that most variants follow the trend to increase both the negative skew around $r/R = 0.5$ and the positive skew at the tip. However, both the variant with best efficiency and the one with best pressure pulse reduction show only a small variation in that direction.

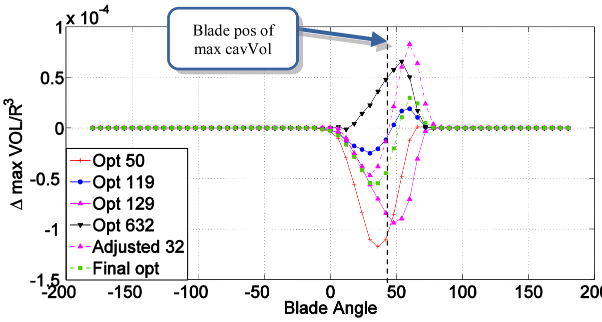
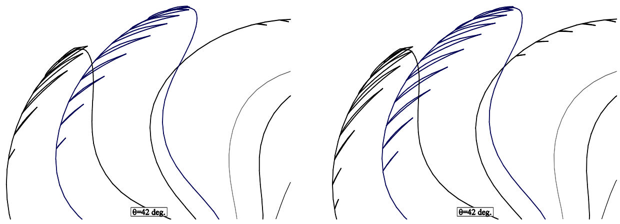


Figure 12 Cavity volume at each blade position compared with the initial solution



(a) (d)

Figure 13 Final propeller performance in ship wake: (a) opt 50, (b) opt632

The solution of the *final* optimisation shows in fact a contrary decrease in skew at the tip.

Figure 12 gives an overview of the change in cavity volume for five selected variants compared to the initial design. As expected the variants *opt 129* and *opt 50*, with the lowest pressure pulses, show a smaller cavity volume along all calculated blade positions. Otherwise a reduction could not be promoted for all blade positions. It is rather a shift in cavity volume towards later positions visible. However, the maximum cavity volume is not necessarily to be reduced.

The most interesting variants (*opt632* and *opt 50*) are shown in Figure 13. These variants are opposite in maintaining one objective and improving the other (compare Table 3). Variant *opt50* shows a significant cavity volume reduction for all calculated blade positions and thus an expected reduction in maximal pressure pulses. However, variant *opt 632* managed to maintain the pressure pulse level despite a significant increase of cavity volume. This might be related to a different shape of the cavity. The maximal cavity length and the maximal cavity centroid are reduced further for *opt632*. It appears that these constraints are also strongly related to the objectives. Both variants show almost the same pitch, chord and skew distribution but differ in essentially in camber and thickness whose influence on the cavity length and on the cavity centroid is of high importance according to the SA. The chord reduction from *opt 632* is favourable for its high efficiency and the increase in cavity volume. But the intense cavity volume reduction of *opt 50* cannot be explained by the further reduction of chord length or the increase in thickness and camber.

6 CONCLUSION

The presented work intended to investigate the impact of geometry parameters on the objectives and constraints in a propeller blade optimisation. The optimisation approach itself showed to be able to improve the geometry regarding both the objectives and cavity constraints, despite having a very good baseline design. Although the improvement turns out to be rather modest regarding the propeller efficiency, the reduction of pressure pulses was substantial compared to the initial design. This is possibly explained by having a focus on constraints that influence the pressure pulses. The design balances however on a thin line between improvement and worsening, which is essentially the result of tight limits for the thrust coefficient and the fact that the baseline design was already optimised. The pitch adjustment that was performed on off-design propeller variants did not entirely help to conquer this restriction along the Pareto front variants. The adjustment was only useful when the pitch could be reduced.

The second optimisation approach with reduced input parameters showed a significant improvement on the convergence of the algorithm and thereby a reduced time for optimisation. The parameters with the major impact can thus be considered to be successfully determined by the SA. In fact, the final geometry from the 2nd optimisation shows essentially the same geometric trends as the variants from the 1st run. Variants created for a SA could possibly be reused as the first generation of an optimisation algorithm and would reduce the time for optimisation further. However, interaction effects could not entirely be resolved; the chord impact for instance remains unsolved. This is according to the SA of less importance, but almost all of the Pareto efficient variants show a significant reduction in chord length.

The general design procedure is simplified for the automated optimisation by ignoring effects like off-design performance and detailed structural stresses analysis according to Rolls-Royce internal design criteria. The outlined optimisation procedure may therefore be rather seen as a supporting tool for the propeller designer to find quicker interesting variants. The SA has shown to be a helpful method to narrow down input parameters and can be quite beneficial in optimisation procedures.

REFERENCES

Burnside, O. H., Kana, D. D., et al. (1979). 'A design procedure for minimizing propeller induced vibration in hull structural elements'.

Deb, K., Pratap, A., et al. (2000). 'A Fast Elitist Multi-Objective Genetic Algorithm: NSGA-II'. IEEE Transactions on Evolutionary Computation **6**.

Giglioli, N. (2008). SimLab 2.2 – Reference Manual, European Commission - IPSC.

Han, K.-J. (2005). Numerical optimization of a propeller in a given wake and behind a ship. Göteborg, Chalmers University of Technology.

Harries, S. (2003). Geometric Modelling and Optimization. OPTIMISTIC Optimization in Marine Design. L. Birk and S. Harries. Berlin Mensch & Buch Verlag.

He, L., Chang, S., et al. (2010). MPUF-3A Version 3.0. Austin, University of Texas.

Hilleary, R. (1966). The tangent search method of constrained minimization. Montery, United States Navak Postgraduate School.

Kerwin, J. E. (1961). The Solution of Propeller Lifting Surfrace Problems by Vortex Lattice Methods. Cambridge, Massachusetts Institute of Technology.

Kerwin, J. E., Kinnas, S., et al. (1985). 'Experimental and Analytical Techniques fir the Study of Unsteady Propeller Sheet Cavitation'. 16th Symposium on Naval Hydrodynamics, Berkeley, California.

Kinnas, S. (1985). 'Non-Linear Correction to the Linear Theory for the Prediction of the cavitating Flow around Hydrofoils'. Ph.D., Massachusetts institute of Technology.

Lee, C.-S. (1979). 'Prediction of steady and unsteady performance of marine propellers with or without cavitation by numerical lifting-surface theory'. Ph.D., Massachusetts institute of Technology.

Lophaven, S., Nielsen, H., et al. (2002). DACE A Matlab Kriging Toolbox. Lyngby, Technical University of Denmark.

Lu, N., Svennberg, U., et al. (2012). 'Numerical Simulations of Cavitating FLow on Marine Propeller'. 8th International Symposium on Cavitation, Singapore.

Mishima, S. (1996). 'Design of Cavitating Propeller Blades in Non-Uniform Flow by Numerical Optimization'. Ph.D., Massachusetts Institute of Technology.

Myers, R., Montgomery, D., et al. (2009). Response Surface Methodology: Process and Product Optimization Using Designed Experiments (Wiley Series in Probability and Statistics), Wiley.

Sacks, J., Welch, W., et al. (1989). 'Design and Analysis of Computer Experiments'. Statistical Science **4**(4).

Saltelli, A. & Bolado, R. (1998). 'An alternative way to compute Fourier amplitude sensitivity test (FAST)'. Computational Statistics & Data Analysis **26**(4).

Saltelli, A., Tarantola, S., et al. (1999). 'A Quantitative Model-Independent Method for Global Sensitivity Analysis of Model Output'. Technometrics **41**(1).

Sun, H. & Kinnas, S. (2007). HULLFPP, HULL Field Point Potential. Austin, University of Texas.

Vesting, F. & Bensow, R. E. (2011a). 'Propeller Blade Optimisation applying Response Surface Methodology'. 14th Numerical Towing Tank Symposium (NuTTS'11), Southampton.

Vesting, F. & Bensow, R. E. (2011b). 'Propeller Optimisation Considering Sheet Cavitation and Hull Interaction'. Second International Symposium on Marine Propulsors, Hamburg.