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Aspects of Propeller Developments for a Submarine

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ABSTRACT

Design and development of propellers for submarines are in some ways different from propellers for surface vessels. The most important demand is low acoustic signature that has priority over propeller efficiency, and the submarine propeller must be optimized with respect to acoustics rather than efficiency. Moreover the operating conditions of a submarine propeller are quite different. These aspects are discussed as well as the weighing of the various propeller parameters against the design objectives.

The noise generated by the propeller can be characterized as thrust noise due to the inhomogeneous wake field of the submarine, trailing-edge noise and noise caused by turbulence in the inflow.

The items discussed are demonstrated in a case study where a propeller of the Kappel type was developed. Three stages of the development are presented, including a design of an 8-bladed propeller where the thrust fluctuations as well as the thrust noise were significantly reduced relative to a 7-bladed propeller. Results of measurements are in good agreement with calculations.

Keywords

submarine propeller, propeller acoustics, Kappel propeller, propeller noise.

1 INTRODUCTION

Design and development of propellers for submarines are in some ways different from propellers for surface vessels. The most important requirement for a submarine propeller is a low acoustic signature. In the design process the steps in the design procedure include estimates of speed and power and weight as the usual standard procedure. The main feature for the design of an acoustically optimised propeller is the frequent check of its acoustic properties. There are generally four conditions that must be considered:

- deep diving, turning and diving,
- periscope depth, diving and with acceleration,
- surface operation and high acceleration mode,
- wind milling, near the surface.

The noise criteria to be considered include thrust noise at blade rate, trailing-edge noise, turbulence noise and structural noise.

The parameters that can be varied during the design process are: diameter, blade number, skew and rake, circulation distribution (pitch and camber) and trailing edge geometry. For submarines there are generally fewer restrictions on the diameter than for normal surface ships and increasing diameter means decreasing specific propeller thrust and higher average inflow velocity.

In the present case several designs were examined. Parameters varied include diameter, number of blades, blade shape (skew and rake and in particular tip geometry) and propeller turning rate. However, the paper focuses on the development and application of propellers of the Kappel type (non-planar lifting surface). Results of calculations, model test and full-scale tests are compared.

2 DESIGN OBJECTIVES

The naval submarine is a complicated vessel built to fulfill a multitude of conflicting requirements. Leaving aside the crew and weaponry contained and supported by the submarine, some of the objectives to be targeted by the overall vessel and by the propulsion system and its propeller are:

- low acoustic, optical, electromagnetic, thermal and communication signatures,
- large operational window with respect to endurance, speed and depth,
- high manoeuvrability in surfaced and in particular in submerged condition,
- best possible form and arrangement of hull and control surfaces to achieve a low hydrodynamic resistance and a smooth hull wake,
- propeller with low excitation level with respect to noise and vibrations,
- propeller totally free of cavitation with adequate margins,
- propeller with high efficiency.

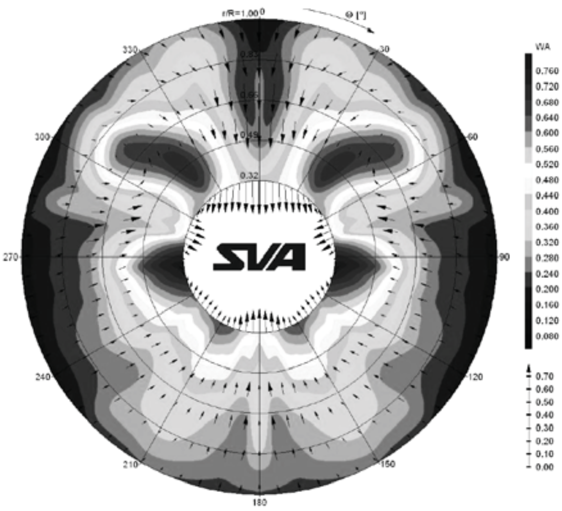

Figure 1: Typical U-boat wake. Low-velocity regions can be seen close to the hub at 1.30 and 3 o'clock positions and symmetrically at the port side. A remarkable region of relatively high velocity is present around 12 o'clock for the outer radii.

A typical submarine wake is shown in Figure 1. It can be seen that it differs significantly from most single-screw surface ship wakes being without the usual low-velocity region in the upper part of the propeller disk, but with remarkable influence of the control surfaces just upstream of the propeller. This, in combination with the demand for adequate cavitation-free margin of propeller operation together with the strict requirements to noise, as outlined in Figure 2, is a challenge for the propeller designer.

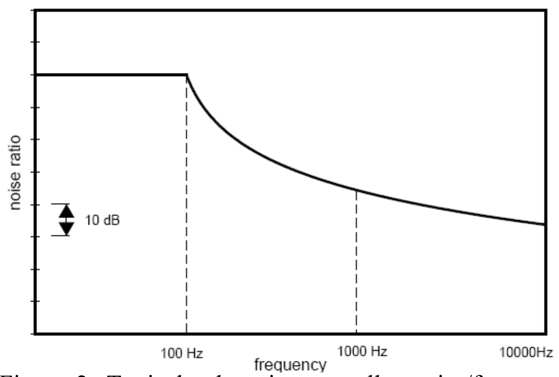

Figure 2: Typical submarine propeller noise/frequency limit.

3 DESIGN PROCEDURE

The design procedure of the propeller should ideally include feedback to the design of the submarine hull and its control surfaces. The progress is iterative and can be illustrated with the classical design spiral. A similar design spiral can be outlined for the propeller design, cf. Figure 3. It illustrates the main feature in the design process of an acoustical optimized propeller: the frequent check of the acoustics. Optimization can be achieved by defined parameters which can influence each other. All design parameters should be considered simultaneously as far as possible. The evaluation of a solution and its possible consequences for the general design is done under the design step designated "feedback analysis".

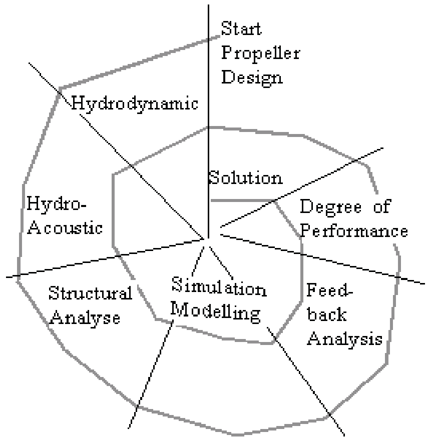

Figure 3: Design spiral for submarine propellers.

3.1 Design matrix

Whereas the design spiral describes the design as a process the objectives and parameters must be specified. The overall requirements to the submarine leads to objectives specifically related to the design of the propeller. These objectives are to be achieved in each of the operating conditions mentioned in the introduction of this paper.

To meet the objectives the submarine propeller must be carefully optimized and balanced with respect to the design parameters available. Some of the implications of this process can be demonstrated if the objectives defined and the parameters available are seen as a design matrix, cf. Table 1.

4 DESIGN CONSIDERATIONS

The issues presented in the design matrix in Table 1 lead to a number of detailed design considerations.

4.1 Cavitation margin

Most surface ships experience propeller cavitation during normal operation. The design effort for surface ship propellers is therefore directed towards avoidance of harmful cavitation in way of erosion and towards moderate levels of propeller excited noise and vibration. However, propeller cavitation must be completely avoided for a submarine in submerged condition in order to secure the lowest possible noise signature. For this reason, for a submarine in submerged condition, the cavitation margin that determines the non-cavitating operating regime is very important. In general, the cavitation margins are defined by inception of:

Table 1 Design matrix. Influence: X little or none, XX moderate, XXX strong.

PARAMETERS	OBJECTIVES							
	cavit. free range		low noise and vibration level				high efficiency	stress limit
	cavit. margin, general	cavit. margin tip	excitation	1.&2. order nat. freq.	TE noise	anti-sing.		
orthogonal blade length	XX	XXX	XX	XXX	X	X	XX	XX
section profile	XX	X	X	X	X	X	X	XX
circulation distribution	XXX	XXX	X	XX	X	X	XX	X
pitch distribution	XXX	XXX	X	XX	X	X	X	X
camber distribution	XXX	XXX	X	XX	X	X	X	XX
skew	XX	X	XX	XX	X	X	XX	X
area ratio	XX	X	XX	XX	X	X	XXX	XX
area distribution	XX	X	XX	XX	X	X	XX	XX
diameter	XX	XX	XX	XXX	X	X	XX	XX
RPM	XX	XX	XX	X	XX	X	XX	XX
blade number	X	XXX	XXX	XXX	X	X	X	XX
thickness ratio	XX	X	X	XX	X	XX	X	XXX
trailing edge thickness	X	X	X	X	XXX	XX	X	XX
anti-singing edge form	X	X	X	X	XX	XXX	X	X
material	X	X	X	X	X	XXX	X	XX

- suction-side cavitation
- suction-side tip-vortex cavitation
- pressure-side cavitation
- pressure-side tip-vortex cavitation
- hub-vortex cavitation

Suction and pressure-side cavitation can normally be avoided by allowing adequate room in the classical cavitation bucket. This may lead to a thicker section profile than used for a comparable cavitating propeller of a surface ship.

Tip-vortex cavitation is – apart from ambient pressure less vapor pressure – dependent on the vortex intensity and the viscosity of the fluid. In turn the vortex intensity depends on the gradient of circulation at the outer part of the propeller blade. Submarine propellers are therefore generally tip relieved in order to obtain sufficient margin against tip-vortex cavitation. This leads to a less-than-ideal circulation distribution with respect propeller efficiency. As tip-vortex cavitation is also dependent of viscosity a correction of the results observed in the model tank will have to be applied to arrive at full-scale expectations, for example according to McCormick. The formation of tip-vortex cavitation observed in model tests seems very dependent on local tip geometry. An explanation could be that the amount of boundary-layer material ending up in the vortex core depends on the blade tip geometry. This would in turn have an effect on the cavitation margin as more boundary-layer material would increase the viscous and turbulent boundary core.

The hub vortex consists of the combined blade root vortices. Similar to the tip vortex, the hub vortex is dependent on the circulation gradient at the blade root. The intensity of the hub vortex can be reduced by relieving the blade loading towards the root. Similar to tip relieving this leads to reduction in propeller efficiency. Alternative means to suppress hub vortex cavitation may be used by applying a boss cap with small lifting surfaces which reduces the rotation of the hub vortex core. Furthermore, hub vortex cavitation can be suppressed if the boss cap is given a form that will generate enough turbulence to increase the vortex core and thereby avoid cavitation.

Cavitation performance for submarine propellers is generally illustrated in a diagram presenting the cavitation number σ_N as function of the trust loading K_T at which the cavitation starts to occur. This presentation is not directly suitable when comparing propellers where parameters such as propeller diameter are different. Instead, it is suggested to compare the relative margin against cavitation $100\Delta K_T/K_T$ as a function of the operational depth T_{pc} for a given speed, where K_T is the design value and ΔK_T is the difference between the design value and the cavitation limit of K_T, cf. Figure 4.

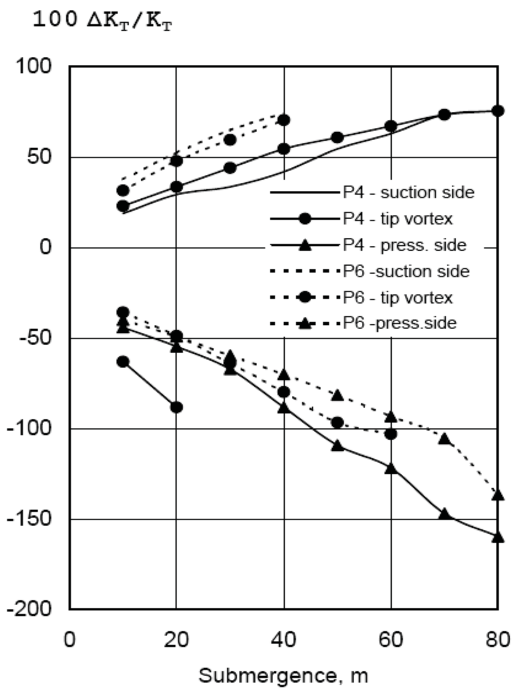

Figure 4: Relative margin against cavitation, i.e. cavitation starts at the deviations in thrust coefficient shown. The results are based on model tests without scale corrections for propellers 4 and 6 discussed in Section 6.2.

4.2 Reduction of wake-induced propeller forces

The most important parameter with respect to propeller-induced forces is the wake field itself which for many reasons should as fair as possible, be it surface ships or submarines. However, with a given wake field the number of propeller blades can probably be considered the most important issue. Increasing the number of propeller blades will reduce the unsteady force on each propeller blade, but not necessarily the total unsteady force. An example of unsteady force calculations with a panel method for propellers with various geometries and blade numbers are discussed in section 6.3.

Increase of the propeller diameter may increase or decrease the unsteady forces depending on the radial distribution of the unsteadiness in the wake field. An example of variation of unsteady forces with propeller diameter calculated by a panel method is shown in section 6.3.

4.3 Skew, pitch and camber distribution

The application of skew can reduce in particular the first-order thrust and torque fluctuations and improve the cavitation behaviour as commonly seen in surface ships. However, a fairly large skew angle is needed to reduce torque and thrust fluctuations significantly. Large skew angles lead to fairly complicated higher-order flexural modes of the propeller blades – not to mention the blade stresses when the propeller is going astern - for which reason large skew angles are often avoided in case of submarine propellers.

4.4 Orthogonal blade length and circulation distribution

The circulation distribution has been discussed in 4.1 with respect to load relieving of tip and root in order to obtain sufficient margin against cavitation. However, the application of "non-planar lifting surfaces" (Andersen *et al*. (2005)) changes the circulation significantly. It is no longer meaningful to present the circulation as a function of the radius, instead circulation as a function over the orthogonal blade length is used. This length is measured orthogonally to a surface of helicoidal streamlines passing the propeller blade. For a conventional propeller with a radial generator line the orthogonal blade length is that of the radial line independent of skew, whereas the orthogonal line with or without skew might be about 10 per cent longer for the propeller with non-planar lifting surfaces. A typical circulation distribution for a Kappel propeller with non-planar lifting surfaces and a conventional propeller is shown in Figure 5. Note that gradient or derivative of the circulation distribution and the maximum circulation is smaller in case of the Kappel propeller. Both facilitate the adjustment of the load distribution with respect to increase of cavitation margins and blade-area distribution with respect to reduction of unsteady forces.

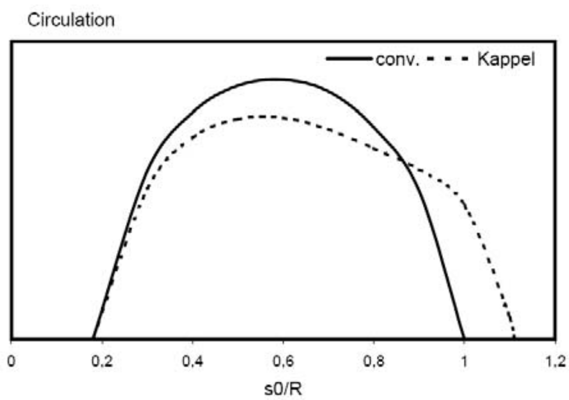

Figure 5: Spanwise circulation distribution of a conventional and a Kappel propeller designed for the same task. S_0 is the length parameter along the orthogonal blade.

5 ACOUSTICS

The effectiveness of a submarine is highly dependent upon its noise signature, the special task of the boat giving it mainly a passive role and control function. The hydrodynamic flow noise dominates in particular the performance of the sonar system. The own noise of the boat correlates with the detection range, with respect to detecting other ships and to being detected. Three types of noise can be identified:

- Thrust noise, dominating the noise level in the low frequency range (<100 Hz),
- Trailing edge noise (200-1000 Hz),
- Broad band noise (100-1000 Hz), caused by turbulence in the inflow.

5.1 Thrust fluctuations

The oscillating thrust of the propeller is probably the dominating acoustic source. On the other hand thrust fluctuations are not the only source as far as noise is concerned. Measurements in full scale indicate differences from theoretical calculations. In general, a reduction of thrust fluctuation by 50 per cent yields a reduced value for the noise level of 6dB which theoretically halves the detection range of the submarine. The acoustic level (dipole source) is proportional to the harmonic order m, blade-number Z, turning rate n, and the m-harmonic fluctuating force and consequently the diameter, skew and number of blades of the propeller must be selected with care.

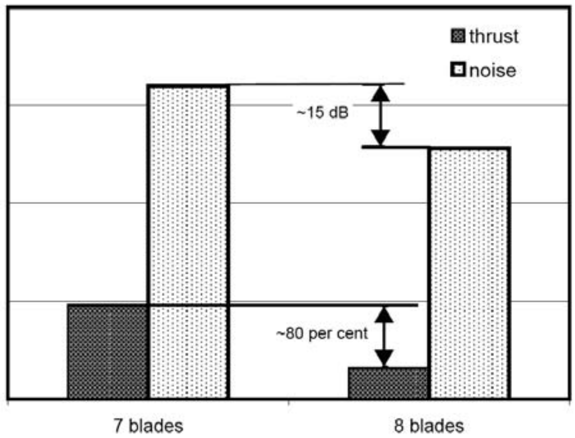

Figure 6 Reduced noise (80 per cent reduction of thrust fluctuation) for the 8-bladed propeller relative to the 7-bladed propeller.

This is illustrated in Figure 6 where a large reduction in the thrust-fluctuation noise has been obtained by increasing the blade number from 7 to 8. The reduction in thrust variation is calculated by the boundary-element method, cf. Table 3, and the noise predicted by the procedure by Ross (1986) on the basis of these results. These results are in accordance with measurements, cf. Figure 10.

Although thrust fluctuations can be reduced by a good propeller design it is important to emphasize that the wake optimization should begin early in cooperation with the propeller designer. A poor flow field is not a good baseline for the process of minimizing noise.

5.2 Trailing-edge noise

The trailing-edge noise should not be neglected. For submarines the whole noise spectrum is of concern, whereas for surface ships the immediate problem is propeller singing, cf. Carlton (2007). For this reason submarine propellers are rarely provided with anti-singing edges, unless there are specific problems.

Theoretical work on trailing-edge noise has been done by Lighthill (1952) and Blake (1986), and in addition measurements exist, cf. Carmargo *et al.* (2005). These measurements show clear evidence of vortex shedding and correlation with the noise level, indicating that the frequency increases somewhat with flow speed and that the harmonic content also increases with angle of attack of the blade sections.

The concentrated fluctuation intensity may be expressed by (1st approach by Ross (1987)) $I \approx 5.6 \cdot 10^{-10}$. For a blade section the typical sound level is in the range of 27dB ($f \approx 350$ Hz). The Strouhal number is estimated as 0.2 for all conditions.

In a case with a full-scale propeller with a blunt trailing edge the noise level was nearly 50dB indicating most probably induced trailing-edge noise in accordance with the results of Figure 7.

The overall blade shaping, the trailing-edge geometry and the boundary layer in the local region are decisive for the trailing-edge noise, cf. Blake (1986). Reshaping the trailing-edge region altogether shows some progress. Wang *et al.* (2006) show results of a numerical optimization of trailing-edge noise where a substantial reduction in the vortex shedding was obtained with a corresponding improvement in the acoustic spectrum, in particular in the low-frequency range.

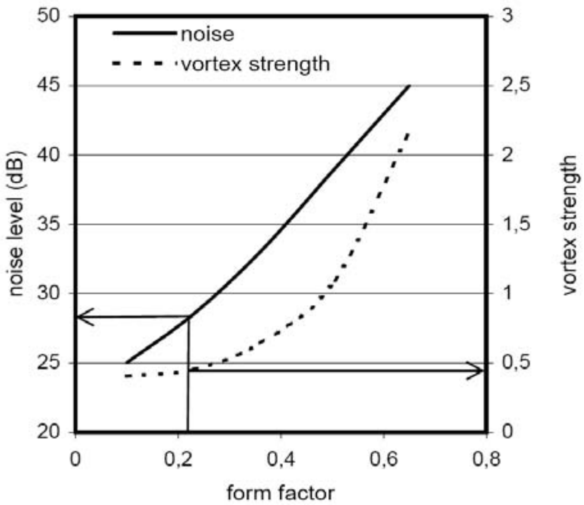

Figure 7 Trailing-edge noise generation and vortex strength as function of trailing-edge geometry. The Kappel propeller examined generally all have a form factor of 0.22 as indicated.

In Figure 7 results of a simple analysis is presented of the correlation between trailing-edge geometry, trailing-edge vortex strength and noise. The analysis is made following the procedure by Blake (1986) for two-dimensional sections where the trailing edge is varied locally, from very blunt shapes to very sharp forms. The shapes are described by a form factor. From the figure it is seen that there is a correlation with the trailing-edge vortex strength, the more blunt trailing edge giving more noise.

In general, the noise starts at frequencies larger than 200Hz up to 1000Hz, and the strength varies with the blade section radius, the wake harmonics and partly with the local coherency of the vortices. For high Reynolds numbers (larger that 10^6) the situation in unclear.

In the worst case singing will occur where the trailing-edge noise gives strong tonal spectra and blade structural regions synchronise their vortex shedding in the so-called "lock-in effect". Generally, the structural dynamic behaviour should be taken into account in the concept of propeller design. The blade geometry influences the eigenmodes, but the highly damped material "Sonoston" helps in some cases to reduce the peak magnitude somewhat.

5.3 Inflow-induced noise

The inflow to the propeller is a stochastic flow field superimposed the steady inflow field. The turbulence intensity and the integral length scale are decisive values. The inflow turbulence increases the noise-spectrum, especially if the turbulence length is equal or close to the blade distance. Although this phenomenon has not been experienced with open propellers it occurs for pumpjets with high blade numbers.

5.4 Perspective

For further developments of understanding of the flow-induced noise, as introduced in this paper, a viable and promising alternative would be systematic acoustic measurements, for example using "piezo-technique" on the surface of the blade (trailing-edge region), last but not least to verify theoretical calculations. The approach by Lighthill equations (Lighthill (1952)) can be designated as a first estimation. If enhanced predictions are to be made the efforts will increase strongly. More comprehensive software packages (hybrid procedure) exist on the market and use more or less the principles of Lighthill analogies as well. The applicability of this software is demonstrated for some examples, but the applications for the propeller design process are most doubtful. What are needed first are accurate experiments in model and full scale which are essential to scaling the theoretical calculations.

6 EXAMPLE

The development of a propeller for a particular submarine design is described in the following and it demonstrates some of the problems involved in the design process.

6.1 Initial design stage

For the initial stages of design four designers were invited to present their best proposal for the submarine propeller. The propellers were tested at Potsdam Model Basin, (Schiffbau-Versuchsanstalt Potsdam, SVA), Germany, in their cavitation tunnel in open water and behind a dummy

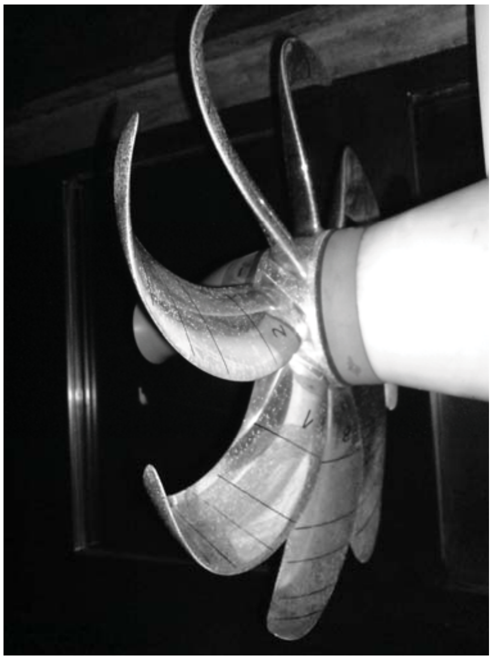

Figure 8: Model of Propeller 8, the 8-bladed Kappel propeller as discussed in Section 6.3.

model of the submarine. The initial design stage was followed by a second design stage in which the design restrictions with respect to the first order natural blade frequency were relaxed. Two propellers were tested in the model tank at SVA in the second design stage. Two further designs were tested in the model tank in a third design stage. All propellers are fixed pitch and right-handed. Propellers 4, 6 and 8 were of the Kappel type. The detailed geometries of the propellers were quite different. The main parameters of the eight propeller designs are listed in Table 2 with Propeller 4 as reference. In this paper the particular design work with three Kappel designs will be described even though several other designs were also developed and tested.

Propeller 4 (Kappel) of the first design stage was tested in full scale with the original trailing-edge geometry and with a trailing-edge geometry modified corresponding to an anti-singing edge for a surface ship, sloped from the suction side. This modification reduced the noise level significantly in the frequency range 150 to 350 Hz, as indicated in Figure 9. Propeller 4 showed moderate thrust fluctuations after the modification.

6.2 Second design stage

Based on the model-test and full-scale results of the first design stage and on relaxed conditions with respect to first-order natural blade frequency, two further designs were made in the second design stage. Relaxation of the design requirements made possible a substantial improvement of the cavitation margin and small reduction in the thrust fluctuation. Propellers 5 and 6 (Kappel) were designed in this stage.

Table 2. Propeller designs

	1st design stage				2nd design stage		3rd design stage	
	Propeller 1	Propeller 2	Propeller 3	Propeller 4*	Propeller 5	Propeller 6*	Propeller 7	Propeller 8*
Diameter (relative)	1.06	0.96	0.96	1.0	0.94	1.0	0.94	1.0125
Pitch ratio	0.83	1.02	1.05	1.03	1.04	1.09	1.21	1.09
Skew, degree	13.75	-15.03	22.99	30.8	31.6	29.7	31.4	29.6
Blade area ratio	0.52	0.50	0.76	0.59	0.61	0.59	0.59	0.59
No. of blades	7	7	7	7	7	7	7	8

*Propellers 4, 6 and 8 are of the Kappel type.

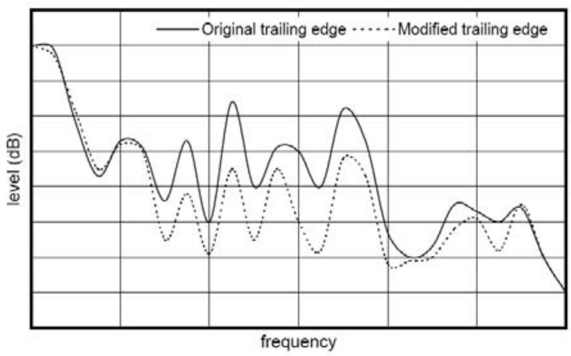

Figure 9: Envelopes of measured full-scale thrust fluctuations for Propeller 4 (cf. Table 2) with original and modified trailing edges.

6.3 Third design stage

The harmonic analysis of the wake of the submarine indicated that reduced propeller excitations might be expected in case a six-bladed and particularly an eight-bladed propeller were selected instead of a seven-bladed propeller. For this reason the propeller forces and moments were calculated for propellers in the behind condition by use of the boundary-element method in the third design stage. The propellers were assumed to be non-cavitating. The calculations were carried out for the seven-bladed versions, Propeller 4, Propeller 6 and furthermore for eight-bladed propellers with diameters (relative) of 1.0, 1.025, 1.05 and 1.1 (versions of Propeller 8). Table 3 gives an overview of forces and moments calculated. According to these calculations the design changes from Propeller 4 to Propeller 6 resulted in a minor reduction of thrust fluctuation. However, the change from seven to eight blades reduces the thrust and torque fluctuations to about 1/5. The fluctuation of the vertical force component is of the same magnitude for the blade numbers seven and eight, whereas the horizontal fluctuation increases 2½ times when changing to eight blades.

The thrust fluctuations were furthermore investigated in the circulating model tank of SVA. The model tank results confirm the significant reduction found by the calculations when changing from the seven to eight blades. The model tests for Propeller 6 (seven blades) and Propeller 8 (eight blades) are shown in Figure 10. The difference between the seven-bladed and the eight-bladed propellers is significant and the difference is more than 10dB which correlates well with the theoretical Lighthill calculation based on the values of the panel calculation.

The optimum diameter with respect to efficiency is found to be in the range 1.0 to 1.025 for the eight-bladed propeller version. The thrust and torque fluctuations calculated by the panel method increases with diameter, whereas the horizontal and vertical force fluctuations decrease marginally. The intensity of the tip vortex will in principle decrease as the diameter is increased, thereby increasing the margin against tip vortex cavitation. However, the cavitation margin in general will decrease as the diameter increases with constant RPM. An eight-bladed propeller with a diameter of 1.0125 (Propeller 8) was designed and tested in the model test facilities of SVA.

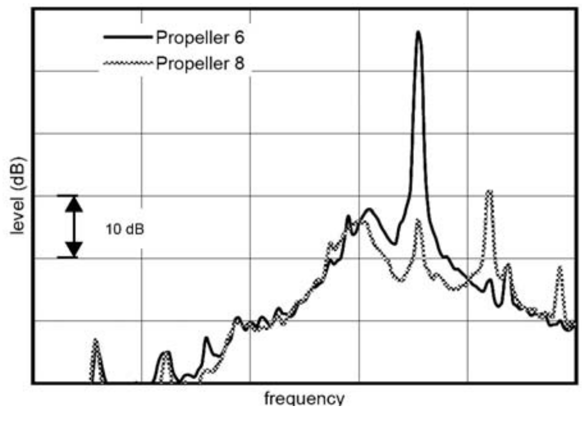

Figure 10. Spectral analysis up to 120 Hz of thrust fluctuations, Propellers 6 and 8 (respectively 7 and 8 blades). The propeller model is turning at 13 rps. The reduction is more than 10 dB at the 1st order blade rate, 91 Hz respectively 104 Hz, when comparing Propeller 6 and 8.

By courtesy of Schiffbau Versuchsanstalt Potsdam (SVA).

Table 3: Total forces and moments acting on propellers in inhomogeneous inflow

Propeller	Propeller 4	Propeller 6	Propeller 8.1	Propeller 8.2	Propeller 8.3	Propeller 8.4
D, (relative)	1.0	1.0	1.0	1.025	1.05	1.1
No. of blades	7	7	8	8	8	8
Kx	0.25942	0.25081	0.25296	0.23448	0.21288	0.16736
Δkx	0.0517	0.0481	0.0089	0.01006	0.00918	0.00918
Δky	0.0093	0.00767	0.00963	00.0086	0.00756	0.00557
Δkz	0.0071	0.00685	0.01724	0.01541	0.01364	0.01074
Mx	0.04326	0.04221	0.04296	0.03880	0.03440	0.02608
Δkmx	0.0076	0.00771	0.00171	0.00183	0.00170	0.00149
Δkmy	0.0032	0.00324	0.00519	0.00470	0.00416	0.00313
Δkmz	0.0051	0.0052	0.00964	0.00895	0.00817	0.00682
Δkx/Kx	0.1993	0.1918	0.0352	0.0429	0.0458	0.0549
Δky/Kx	0.0358	0.0306	0.0381	0.0366	0.0355	0.0333
Δkz/Kx	0.0274	0.0273	0.0682	0.0657	0.0641	0.0642
Δkmx/Mx	0.1757	0.1827	0.0398	0.0472	0.0494	0.0571
Δkmy/Mx	0.0740	0.0768	0.1208	0.1211	0.1209	0.120
Δkmz/Mx	0.1179	0.1232	0.2244	0.2307	0.2375	0.2615
Kx*	0.3750	0.3745	0.0750	0.0901	0.0952	0.1120
Kyz*	0.2551	0.2579	0.4515	0.4541	0.4580	0.4790

$\Delta kx = kx_{max} - kx_{min}$

Kx*=Δkx/Kx+Δkmx/Mx

Kyz*=Δky/Kx+Δkz/Kx +Δkmy/Mx+Δkmz/Mx

7 CONCLUSION

The development work for submarine propellers has been described and the differences relative to surface propellers outlined. The design process has been illustrated for a propeller of the Kappel type applied to a submarine design. The main concern has been a low acoustic signature and one of the means of obtaining this has been using eight blades, relative to seven blades used initially. Theoretical calculations as well as model tests demonstrate that lower thrust fluctuations were obtained accompanied by lower thrust noise.

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REFERENCES

Andersen, P., Friesch, J., Kappel, J.J., Lundegaard, L. & Patience, G. (2005), 'Development of a Marine Propeller with Non-Planar Lifting Surfaces', Marine Technology **42**(3), pp. 144 - 158.

Blake, W. K. (1986). Mechanics of flow-Induced Sound and Vibration, Vol. II, Complex Flow-Structure Interactions. Applied Mathematics and Mechanics, 17-II, Academic Press.

Carlton, J. (2007). Marine Propellers and Propulsion, Second Edition, Butterworth-Heinemann, Elsevier.

Carmargo, H.E., Smith, B.S., Devenport, W. J. & Burdisso, R.A. (2005). Evaluation and Calibration of a Prototype Acoustic Test Section for the Virginia Tech Stability Wind Tunnel, Report VPI-AOE-294, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.

Lighthill, M. J. (1952). 'On Sound Generated Aero-dynamically, I. General Theory'. Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences **211**(1107) (Mar. 20, 1952), pp. 564-587.

Ross, D. (1987). Mechanics of Underwater Noise, Peninsula Publishing.

Wang, M., Marsden, A.L. & Moin, P. (2006). 'Computation and Control of Trailing-Edge Noise', Proceedings of the 26th Symposium on Naval Hydrodynamics, Rome, Italy.