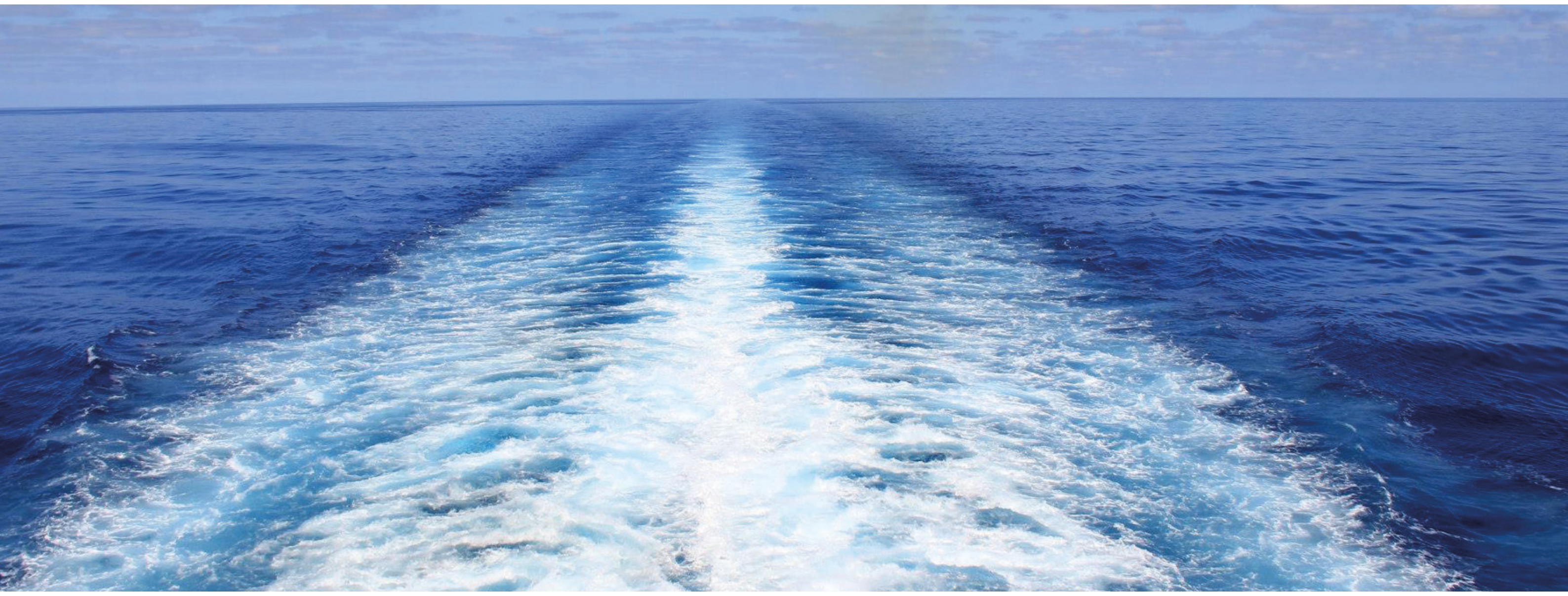
Propeller design by means of multiobjective optimization: **CP propeller test case**



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1. Introduction

Propeller design has evolved significantly in the last few years, with the introduction of numerical methods which can provide an ever improving assessment of propeller characteristics, considering propeller non stationary functioning and cavitating behavior, not only in correspondence to the usual design conditions, but also to off-design conditions. This assessment has become widely adopted, with numerical methods being able to predict propeller characteristic curves (and cavitating behavior) in correspondence to a wide range of advance coefficients. Modern propeller requirements involve many different characteristics, not limiting only to maximum efficiency, but considering also propeller cavitating behavior and, more and more, its side effects, in terms of radiated noise and pressure pulses. This is evident with the ever-increasing demand for improvement of comfort onboard and discussions about radiated noise problems, especially in proximity of protected areas.

In recent years, the interest towards the problem of radiated noise has led the EU to fund some cooperative projects, i.e. SILENV, AQUO and SONIC, whose activities were concluded at the end of 2015. In the context of the first project, UNIGE was involved in the analysis of different ways to reduce underwater radiated noise; since the marine propeller, when cavitating, may become the most significant noise source of a ship, a large part of the work was devoted to the application of a design procedure in which in-house panel codes are coupled with the modeFRONTIER, a multiobjective optimization software. This procedure had already been proposed in (Gaggero, S. and Brizzolara, S. 2009. Parametric CFD Optimization of Fast Marine Propellers FAST 2009), however in the context of this project it was also possible to test it against a real case study and, most important, to validate the results by means of an experimental campaign carried out at Genoa University Cavitation Tunnel.

In particular, the test case is represented by a CP propeller originally installed onboard a RORO-Ferry ship; the peculiar propulsion arrangement of the ship is characterized by having an almost constant revolution rate of the propeller, achieving different operational speeds by means of propeller pitch reductions. In the optimization loop, consequently, two very different working conditions were considered, i.e. the usual design condition at maximum speed and a very reduced speed, obtained at constant RPM and reduced pitch. The two conditions are characterized by very different cavitating behavior, with presence of back sheet cavitation and tip vortex at maximum speed condition and of vortex from sheet face and sheet face cavitation at reduced pitch condition. The latter, in particular, resulted in noise and vibration problems in correspondence to this operating condition, as remarked by the shipowner. As a consequence, the scope of the optimization activity was a new design with the main attention given to the reduced pitch, with the aim of reducing propeller radiated noise, trying contemporarily to keep cavitation extent as low as possible at maximum speed and maintaining propeller hydrodynamic characteristics (with particular attention to propeller efficiency). The optimization strategy is briefly described in section 2, while in section 3 the actual optimization activity is presented. Finally, in section 4 the results of the experimental campaign carried out in order to validate the results are reported.

2. Theoretical background and optimization setup

Traditional propeller design methods are based on lifting line and lifting surface codes; their utilization has been established for a long time and form, even nowadays, the most used tool for propeller designers. Nevertheless, these methods cannot be used directly for a propeller, which needs to be designed for very different working conditions, as the one considered in this work. From this point of view, coupling of panel codes with optimization algorithm can represent an efficient alternative to the classical approach for the designer, as presented in (Gaggero et al. 2009).

As it is well known, panel codes are usually adopted as a propeller analysis tool, and not for design purposes. However, their coupling with multiobjective optimization algorithms allow their use for design purposes. The main advantages of this approach are that panel codes are capable of capturing better propeller performances, allowing to include also limited and local variations, which could be hardly considered with traditional tools. Moreover, panel codes may allow to consider (at least with a level of accuracy which allows a comparative analysis of different geometries) also off-design conditions, like those related to the reduced pitch proposed in present work; finally, the multiobjective algorithm may allow to consider contemporarily very different working conditions, optimizing them contemporarily.

An accurate description of the panel code utilized in this work may be found in Gaggero et al (2009), and is here omitted for the sake of brevity. In order to apply systematically the panel code inside the optimization loop, a robust parametric representation of the propeller geometry (Gaggero et Al. 2009, Brizzolara, S., Gaggero, S. and Grasso, A. 2009.

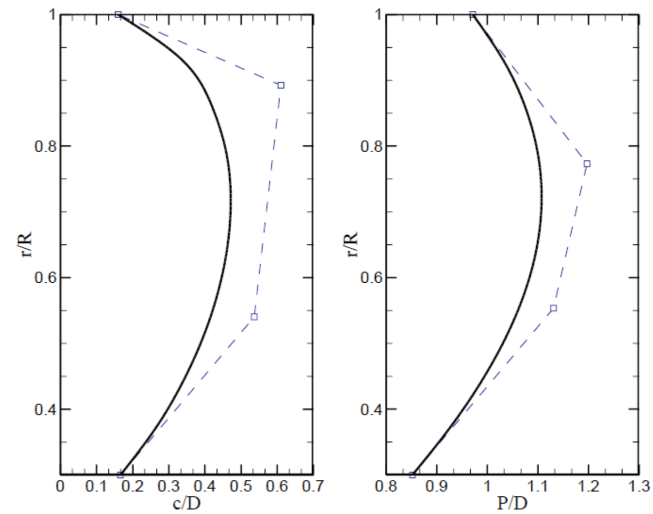

Fig. 1 - B-Spline representation of radial distributions of chord and pitch. [Bertetta, D., Brizzolara, S., Gaggero, S., Viviani, M., Savio, L. 2012 "CP propeller cavitation and noise optimization at different pitches with panel code and validation by cavitation tunnel measurements", Ocean Engineering 53 (2012)]

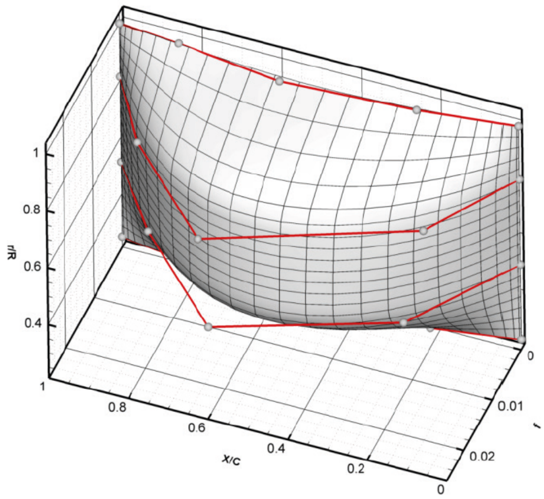

Fig. 2 - Parametric representation of propeller nondimensional mean surface [Bertetta et al 2012]

Parametric Optimization of Open and Ducted Propellers, Propeller/ Shafting symposium 2009) is needed.

The classical propeller design table is, inherently, a parametric description of the geometry itself. All the main dimensions that defines propeller geometry, like pitch, camber and chord distribution along the radius, represent main parameters that can easily be fitted with B-Spline parametric curves, whose control points turn into the free variables of the optimization procedure, as in Figure 1.

For what regard the profile shape, instead of adopting standard NACA or Eppler types, with the same parametric approach it is possible to describe only with few control points thickness and camber distributions along the chord for a certain number of radial sections (or, more consistently, to adopt a B-Surface representation of the mean non-dimensional propeller surface) and include also profiles in the optimization routine (Figure 2).

This was actually the approach utilized in this test case. Once a parametric description of the propeller has been obtained, an optimization loop has been built into the modeFRONTIER environment, and optimization has been carried out by means of the MOGA-II genetic algorithm. At each step of the loop (i.e. for each new generated solution), the potential code is used to evaluate the hydrodynamic characteristics of the propeller (in terms of thrust, torque, efficiency and cavity area/volume).

A fully unsteady calculation of propeller behaviour, although carried out with a panel method, would be excessively time expensive to be included in the optimization loop. As a consequence, as presented in Gaggero (2009), unsteady performances are approximated, with a quasi-steady approach, as the mean (or the sum) of the steady performances evaluated in "N" angular wake sectors, whose mean flow characteristics (axial, radial and tangential velocity distributions along the radius) are taken as the mean radial inflow for a steady computation. A set of constrains is obviously set in order to satisfy the required performances (basically, required thrust at a given speed allowing a shift of $\pm 2.5\%$ to speed up the convergence, and blade robustness), while the objectives of the optimization are an increase of efficiency and a reduction of cavitation extent, at both the design conditions.

3. OPTIMIZATION ACTIVITY

3.1 Original Propeller characteristics

The propeller considered for present study is a conventional 4-bladed CPP for a twin screw ship, whose main characteristics are reported in following table 1, where D is propeller diameter, P0.7 is pitch at 70% radial position, d_{hub} is hub diameter, A_E and A_0 are propeller expanded area and disc area, Z is the number of blades.

Propeller characteristics	
D [m]	4.60
$P_{0.7}/D$	1.08
d_{hub}/D	0.30
A_E/A_O	0.72
Z	4

Table 1 - Propeller characteristics

As anticipated, the propeller is operating at constant revolution rate (about 180 RPM) in correspondence to very different ship speeds (24 and 11 kn) by means of blade pitch angle variation (indicated as "reference pitch" and "reduced pitch" respectively in the following).

3.2 Optimization

For the design of the new propeller, different optimization approaches of increased complexity have been applied, including at each step new propeller parameters. At the end, the parameters investigated were:

- global parameters considered in usual propeller design (chord, maximum thickness, maximum camber and pitch distribution along the radius)
- sectional parameters, i.e. camber and thickness distribution along the chord

The number of free parameters included into the optimization process varies between 21 to 30. In all the cases, an initial population of 300 members was considered and let evolved for 100 generations, for a total number of about 100000 different geometries.

Figure 3, for instance, shows a typical plot of the characteristics, in terms of cavity extension, of all the designed propellers obtained during the optimization having, as free variables, the global parameters plus the profile mean line. The main objectives of the optimization, back cavity area at the design pitch and face cavity area at the reduced pitch respectively, are reported on x and y axis, while bubble radius and colour monitor back cavity area at the reduced pitch (not evident for the original propeller and thus to be avoided) and face cavity area at the design pitch (not evident for the original propeller and thus to be avoided).

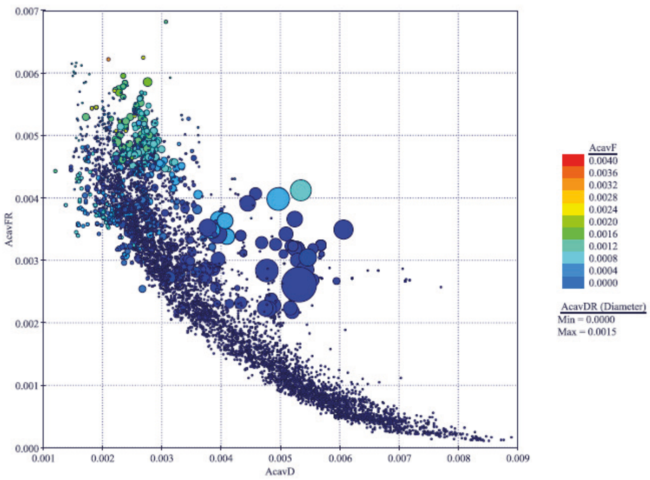

Fig. 3 - Pareto designs for the global parameters plus mean line optimization [Bertetta et al 2012]

In the light of the results of the different optimization approaches, the optimal geometry has been selected among the pareto designs that satisfy the thrust constraints and grant zero face cavitation at the design condition and zero back cavitation at the reduced pitch condition. With respect to the original geometry, all the Pareto designs allow to sensibly reduce face cavitation, only with a minor reduction of back cavitation, consistently with the fact that the original propeller design was centered on maximum speed condition. The new propeller has been selected, among the Pareto solutions, as a compromise between back and face cavitation, having in mind also the side effects of cavitation (in terms of radiated noise). In particular, as mentioned, face cavitation at reduced pitch was definitely the most trying phenomenon for the original propeller, thus it was accepted to have a certain increase for back cavitation at design pitch, obtaining a large reduction of face cavitation. The original and optimized propellers are numerically equivalent in terms of working points. Thrust curves, from which ship speed, at a fixed propeller rate of revolution, depends, are overlapped within the complete range of advance coefficient, as shown for example for the reference pitch in Figure 4. In the same figure, a slight increase in the efficiency is also visible. With respect to the original propeller, face cavitation of the selected optimum propeller was numerically reduced of about 50% (Figure 6) while back cavitation was the 35% greater than the original one (Figure 5).

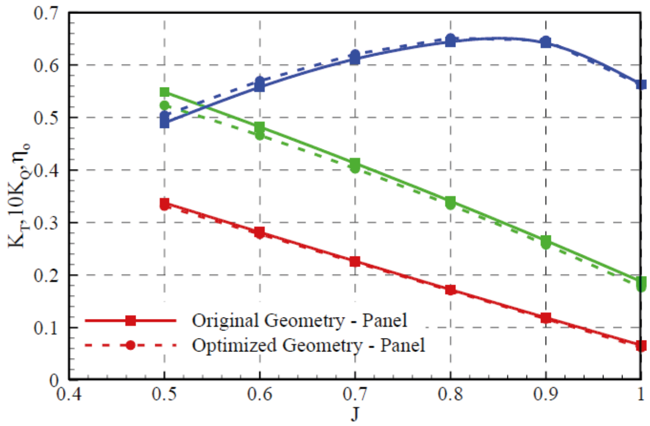

Fig. 4 - Comparison between original and optimized propeller – numerical open water tests – reference pitch [Bertetta et al 2012]

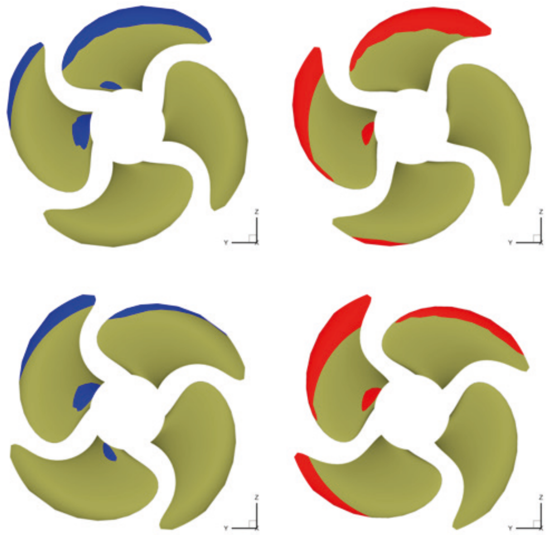

Fig. 5 - Comparison of predicted unsteady back cavity extension (0° - 60°) between original (left, blue) and optimized (right, red) propeller at reference pitch [Bertetta et al 2012]

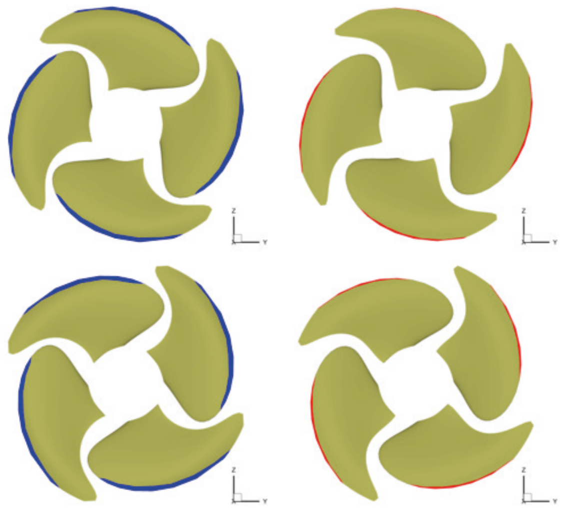

Fig. 6 - Comparison of predicted unsteady face cavity extension (0° - 60°) between original (left, blue) and optimized (right, red) propeller at reduced pitch [Bertetta et al 2012]

4. EXPERIMENTAL CAMPAIGN

4.1 Open Water tests

As a first step in the experimental campaign, propeller open water tests have been carried out at CEHIPAR towing tank for both propellers and pitches, in order to verify their hydrodynamic characteristics. The results, reported in Figures 7 and 8, confirm that the two propellers are equivalent in terms of functioning point at reference pitch (same thrust at same advance coefficient, thus leading to same speed at same RPM), with only a small change (completely acceptable) at reduced pitch. Moreover, in both cases propeller efficiency is increased with the optimized geometry, confirming the numerical results.

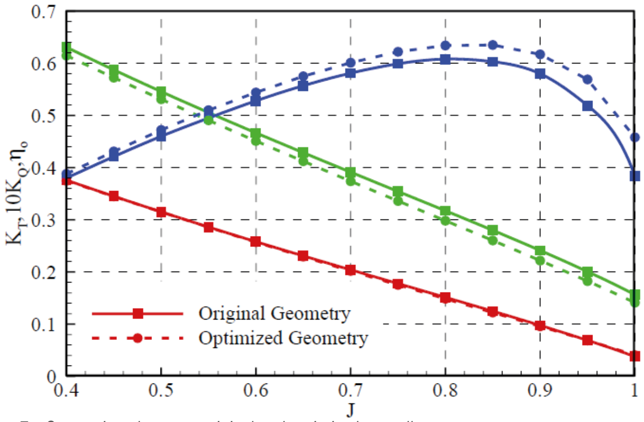

Fig. 7 - Comparison between original and optimized propeller – open water tests – reference pitch [Bertetta, D., Savio, L. and Viviani, M. 2011. Experimental characterization of two CP propellers at different pitch settings, considering cavitating behaviour and related noise phenomena, SMP 2011]

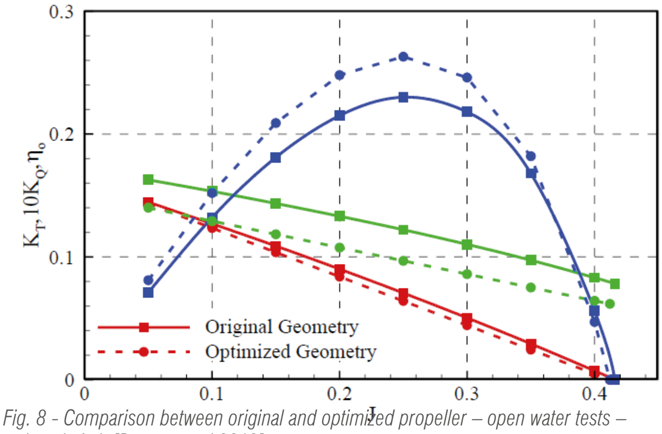

Fig. 8 - Comparison between original and optimized propeller – open water tests – reduced pitch [Bertetta et al 2012]

4.2 Cavitation tests

Cavitation tests were performed at DITEN Cavitation Tunnel, where inception points of various cavitation phenomena have been measured, and cavitation extent observations have been carried out in correspondence to different functioning points. Tests were carried out in correspondence to the nominal wake considered in the design activity and also to a configuration with inclined shaft only, in order to reduce background noise in the tunnel for noise measurements.

In the present work, only the results of the cavitation observations in correspondence to the nominal configuration are reported for the sake of brevity, while complete results are reported in (Bertetta et al 2012).

Results from the optimization activity are confirmed, with slightly worse performances in correspondence to the reference pitch and better performances in correspondence to the reduced pitch. In particular, at reference pitch (Figure 9), a larger chordwise extension of cavitation at higher radiuses towards the tip for the optimized propeller is present; contemporarily, radial extension of cavitation itself is slightly lowered for the optimized propeller. The higher propeller loading results also in the presence of sheet cavitation in correspondence to a wider range of blade angular positions, also outside decelerated wake, confirming the numerical results.

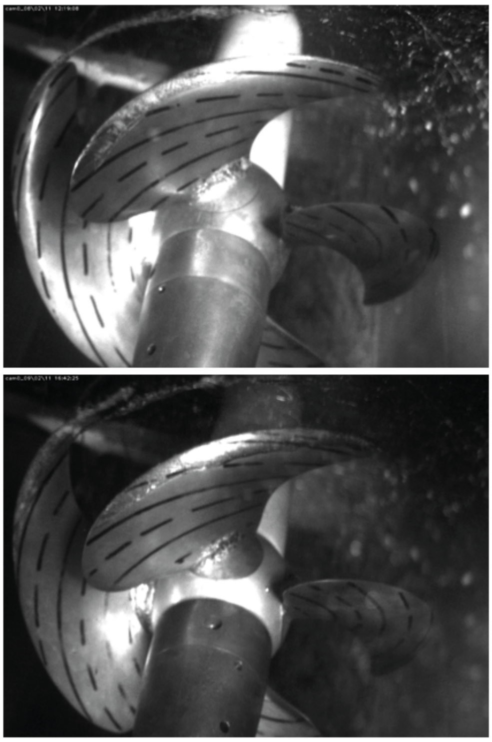

Fig. 9 - Observed cavitation extent at reference pitch Original propeller (above) vs optimized propeller (below) [Bertetta et al 2012]

As expected, the most significant differences are encountered at reduced pitch (Figure 10), as predicted numerically, with a considerable reduction of face related phenomena.

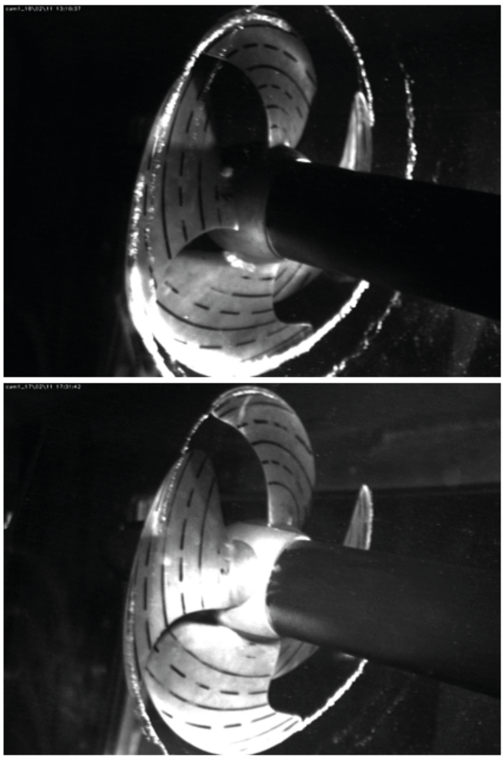

Fig. 10 - Observed cavitation extent at reduced pitch Original propeller (above) vs optimized propeller (below) [Bertetta et al 2012]

4.3 Radiated noise measurements

Radiated noise measurements were carried out in correspondence to a rather large amount of functioning points for both pitch settings and testing conditions (Bertetta et al 2011). The results for the design points only are reported, since the main aim is the validation of the optimization process described above.

The measurements were carried out by means of a Reson hydrophone TC4013, coupled with a Bruel and Kjaer 2635 charge amplifier. The hydrophone has been located inside the cavitation tunnel, outside the direct propeller slipstream. Since water quality is of great importance for cavitation tests and, as a consequence, for noise measurements, during all tests, oxygen content was continuously monitored, as suggested by ITTC, by means of an ABB dissolved oxygen sensor model 8012/170, coupled with ABB AX400 analyser. Constant testing conditions (i.e. oxygen content equal to 40% of the saturation value at atmospheric pressure) were utilised in order to have a fair comparison of the two propellers.

The results are presented in 1/3 octave form. In particular, for each band, the non-dimensional value Kp is evaluated as follows, together with the corresponding level, following:

$$K_p = \frac{p_{rms}}{\rho n^2 D^2} \qquad L_p(K_p) = 20 \log_{10}\left(\frac{K_p}{10^{-6}}\right)$$

in which p_{rms} is the root mean square value of each spectrum component. Measurement have also been scaled at a reference distance of 1 m, using the formulation in accordance to ITTC (1978). Finally, in correspondence to each functioning point the background noise is evaluated by repeating the measurements with all equipment running and with the propeller substituted by a dummy model. Net sound pressure levels may, then, be evaluated as suggested in ITTC procedures. If the difference between the propeller noise and the background noise is lower than 3 dB, no curve is represented in the graphs. Figures 11 and 12 present radiated noise measurements for the two propellers in correspondence, respectively, to the reference and the reduced pitch. As visible, the measurements at reference pitch, due to the background noise, allow to characterize propeller noise only below 1 kHz. Nevertheless, this is the most significant frequency range, where the effect of the cavitating tip vortex is predominant. In particular, it is clear that, consistently with the design assumptions, tip vortex related phenomena are amplified in the case of the optimized propeller, showing an increment of about 4 dB of the peak value. Main differences are due to the vortex related phenomena also in correspondence to reduced pitch condition (in this case face vortex and vortex from sheet face phenomena are present), with opposite effect with respect to design reference pitch condition. In particular, it is clear that the delay of these phenomena results in a considerable reduction (about 9 dB) of the noise spectrum of optimized propeller with respect to the original one. All these results are clearly in line with design goals, with a voluntary slight worsening of propeller behavior in correspondence to the reference pitch in order to reduce significantly noise at the reduced pitch, which was considered as the most important problem for this propeller. This therefore confirms the validity of the proposed design approach.

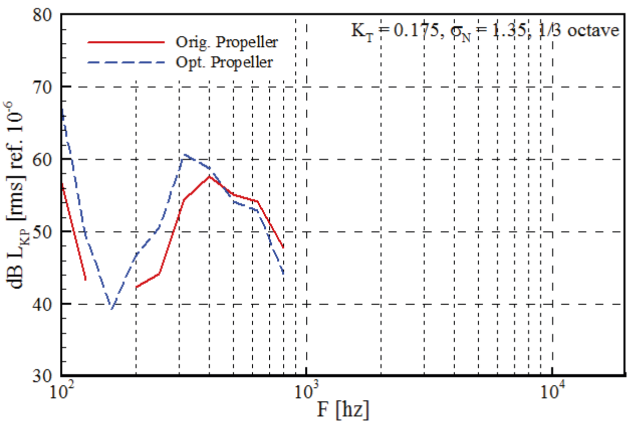

Fig. 11 - Radiated noise measurements at reference pitch [Bertetta et al 2012]

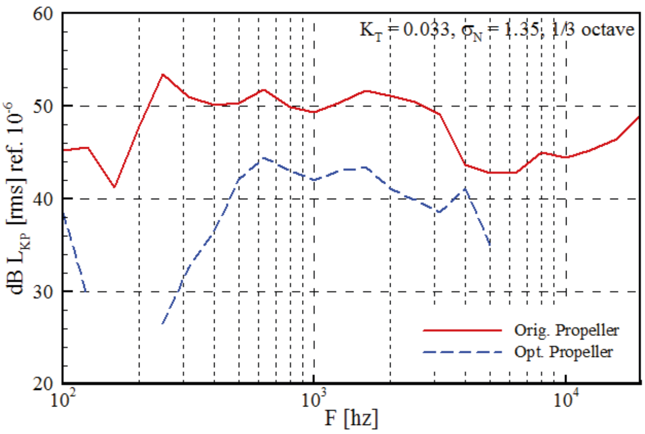

Fig. 12 - Radiated noise measurements at reduced pitch [Bertetta et al 2012]

5 CONCLUSIONS

The design of a CPP propeller has been carried out, utilizing a cavitating panel code for propeller analysis coupled to modeFRONTIER. A challenging task has been considered trying to optimize propeller behavior in correspondence to two very different conditions characterized by reference and reduced pitch.

The goals of the design (improvement at reduced pitch without deteriorating too much the reference condition) were satisfactorily achieved; the successive experimental campaign, moreover, confirmed the predicted propeller behavior. The optimization tool proved to be an efficient mean to improve propeller characteristics, even if in a such problematic case it is difficult to obtain very large improvement at both operating conditions with controllable pitch propellers if operated at constant RPM. In case the same tool is applied to a single operating point, it is expected that much larger improvements may be obtained.

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