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Supersilent Propellers for New Generation Cruise Vessels

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Abstract. A higher level of Underwater Radiated Noise (URN) in the seas around the world is known to be related to the increase of the anthropogenic activities like marine traffic. Much biological research has been carried out, showing that the increased levels of URN can seriously damage the life of marine fauna. Therefore, Classification Societies and International Organizations have developed new rules to limit the underwater noise produced by ships, whose main URN source is propeller cavitation. This paper describes the numerical methods used by Fincantieri to predict the propeller URN by means of Detached Eddy Simulation (DES) coupled with the Ffowcs Williams-Hawkings equation an the techniques developed to delete all types of cavitation on the blade surfaces, both in the silent sailing profile at low speed, and also in the transient condition at higher speed. It has to be highlighted that, for state-of-the-art cruise vessels, the low noise radiation requirements cannot compromise on propeller efficiency. Therefore, this novel propeller design procedure has been developed by employing pieces of optimisation software, where the targets of high propeller efficiency, no cavitation, and very low noise radiation are combined to converge on the best possible blade design. Additionally, a description is also provided of the comparison among the numerical predictions, dedicated URN tank tests, and sea trial measurements; it is shown that the newest Fincantieri vessels with Silent Class Notation are remarkably below the limits set by the URN rules. This target has been achieved also limiting the mechanical noise radiation from engine and other machineries with all necessary noise damping devices.

Keywords. URN, Propeller, Ffowcs Williams-Hawkings

1. Introduction

While there is a worldwide growing attention to carbon dioxide emissions and IMO issued several Regulations like EEDI, EEXI, CII, which bind ships to respecting very precise limits, the same cannot be said for Underwater Radiated Noise (URN). A ship that does not fulfil the new rules for emissions must be derated and sail at lower speed, which results in a decrease in its overall profitability. Binding international regulations are likely to be issued in the near future also for under water ship noise radiation, because the human life is strictly dependant on the health of the seas.

Noise radiated in the oceans does not have the same mediatic impact as, for instance, oil pollution, for which there are infamous photographs of marine seals or seagulls covered in oil. Nevertheless, URN is a silent poison that humans do not perceive, but

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marine fauna is strongly and silently suffering for it. It is an invisible phenomenon, whose seriousness is not yet deeply and fully understood.

Regarding the current URN international regulations, some guidelines as IMO MEPC.1/Circ.906 [1] are available, where general recommendations are given to design more silent ships, but they do not set precise noise limitation.

Therefore, at present the only binding rules to keep the URN under certain threshold are those set by the various classification societies in the silent class regulations like those issued by DNV [2] and RINA [3]. Normally, the silent classes are considering two operational modes: one at low speed, close to 11 knots, and another one, called transient mode, at the contractual service speed. These rules in any case are not mandatory for all ships, but they are setting limits that can be agreed between Owner and Shipyard. If the vessel is expected to sail in protected areas where specific low noise levels should not be exceeded, such rules must be fulfilled.

2. Hull design

The main source of URN produced by ships is propeller cavitation. The noisiest type of cavitation is the one originated from bubbles growing and collapsing on the blade surface, but also the tip vortex has a significant role in the generation of URN. One may then think that, in order to reduce cavitation, just a suitable propeller geometry must be developed.

This approach is limited to only one part of the problem. If a ship wake is showing fluctuating vortices, flow separation, strong speed gradients and high tangential components, even if a good propeller is designed, the final results in terms of URN will be quite poor.

The starting point to achieve low URN levels is to properly design the hull geometry to get a good wake. Although the current trend in cruise ship design is to increase the block coefficient, which could have a negative impact on the wake pattern, a careful selection of the Longitudinal Centre of Buoyancy (LCB) can have an absolutely positive impact on improving the wake. Needless to say, the most hydrodynamically efficient fish and cetaceans do not have a centre of buoyancy located aft, towards the tail, but quite forward, towards the head. The slimmer the tail, the better the body moves in the water as, avoiding flow separation, it recovers almost all of the aft pressure, gaining advantage from the resulting forward-pushing force.

Such concept can be applied to hull design, for instance by using an optimisation tool, which parametrically modifies the sectional area curve: a performance improvement can be achieved by shifting the centre of buoyancy forward, both in terms of ship resistance and especially of wake quality.

The result is that for cruise vessels designed with slim aft body shapes, the residual resistance at full speed can be lower than 15%, the rest being due to friction. Once a good hull is designed by means of an extensive use of optimisation tools, the same procedure can be applied to achieve the optimum shape and orientation of shaft lines and brackets. A systematic variation of shaft and bracket position and orientation should be carried out till the tangential components of the wake are reduced to minimum, and the axial wake pattern is as homogenous as possible, without any deep troughs and with a maximum wake fraction $1\text{-}w$ higher than 0.8.

3. Propeller design

Once the hull and appendages optimisation process has successfully been completed, producing the best possible wake pattern, the design of a silent propeller can start.

Designing a silent propeller with low efficiency is a simple task that can be achieved by reducing its load and the tip vortex strength, while making a silent propeller with high efficiency could seem a difficult goal. Anyway, a low-efficiency propeller, however silent, could not be accepted for a modern cruise vessel, as it would not fulfil the relevant IMO rules regarding CO2 emission reduction. High efficiency and low URN may seem two opposing objectives, difficult to reconcile. However, they can be both achieved at the same time. The first important item to design a silent propeller is the selection of the number of blades. According to the authors' experience, six-blade propellers represent the best compromise for cruise ships.

As discussed, the high lift force on the hull's aft body generated by the correct forward position of the centre of buoyancy and the consequent very low thrust deduction factor t lead to a strong unloading of the propeller. The shallow wake peaks and low tangential components create an optimal situation for the propeller operation. Lower area ratio values can be selected, and, for the largest part of the rotation, the blades are working in an almost shock free entrance condition, thus generating most of the lift with the blade camber itself, and a quite low amount by the angle of attack. This allows to reach a good efficiency, higher than 0.7. Following this design technique, blade surface cavitation can be avoided.

A proper silent propeller can be designed only when, at a service speed close to 80 % MCR, it produces only a very thin tip vortex in true scale, and no other types of cavitations are observed on the blade surface. However, if aiming at URN reduction, attempting at to completely delete the tip vortex in true scale is a wrong design choice. Too large cavitation buckets, which can suppress the inception of cavitation at low speed, can lead to a quick burst of tip vortex cavitation and cavitation on the blades at higher speed. This is not acceptable for a cruise vessel, whose propeller must be silent over the whole speed range.

Another noise-generating type of cavitation is the hub vortex. One of the most effective tools to delete this cavitating vortex is the rudder bulb connected to the propeller hub.

Figure 1 shows a silent propeller at full speed with the rudder bulb and without any trace of cavitation on the blades in model scale.

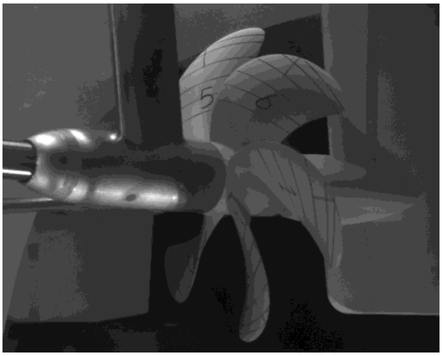

Figure 1: Non-cavitating propeller

Furthermore, the hull pressure pulses are good indicators of a propeller's URN performance at an early design stage. If pressure pulses at 100 % MCR are in the range of 0.2-0.3 kPa for the first harmonic, and close to zero for higher harmonics, it can be expected that the propeller will deliver a low amount of URN also in full scale.

The design process of a silent propeller, suitable for cruise ships, may be summarised in the following steps, which are described in the next Sections of this paper:

- Propeller numerical optimisation.
- Direct URN evaluation.
- URN tank testing.
- Sea trial measurements.

The abovementioned design steps were followed for a specific Fincantieri propeller, and the process is described below.

4. Propeller numerical optimisation

The silent blade design process was driven by a numerical optimisation process, carried out by means of Esteco's commercial optimisation code mode Frontier [4],which allowed to streamline the design expertise into an automated workflow that could handle the propeller geometry definition, run the required calculations to define the propulsive characteristics of each propeller, computing the open water characteristics, pressure pulses, hull integrated forces, cavitation pattern, structural strength, shaft forces and the underwater radiated noise through the ETV (Equivalent tip Vortex) empirical method [5] described in Section 6.

4.1. Geometry preparation and design variables

The typical radial distribution of the propeller parameters as chord, thickness, pitch, camber, skew and rake were reproduced through Bezier curve (one curve for each radial distribution), where the poles coordinates were the variable of the optimisation process.

The Bezier curves for the radial distribution of the pitch, chord, camber, skew and rake were of the 3rd order, while the thickness distribution was a 2nd order Bezier curve. With this arrangement, the design variables were less than fifty, considering that some of the coordinates at the tip and at the root could be treated as constants.

4.2. Solvers

Every propeller geometry was computed by means of a lifting surface code and Boundary Element Method (BEM) piece of software. They were used to calculate the propulsive characteristics and the pressure distribution on the blade to identify the areas where the local pressure would drop below vapour pressure. To avoid any cavitation on all the blade surfaces, a design constraint on the blade pressures was applied. Furthermore, the empirical model ETV was applied to obtain the tip vortex strength and a preliminary prediction of the radiated noise spectrum. Some more precise verifications were introduced in the design loop by means of Reynolds Averaged Navier-Stokes

Equation (RANSE) code calculation, mainly to check with maximum care the margins against the inception of pressure side cavitation, which should be absolutely avoided in any operating conditions, at all rotation angles.

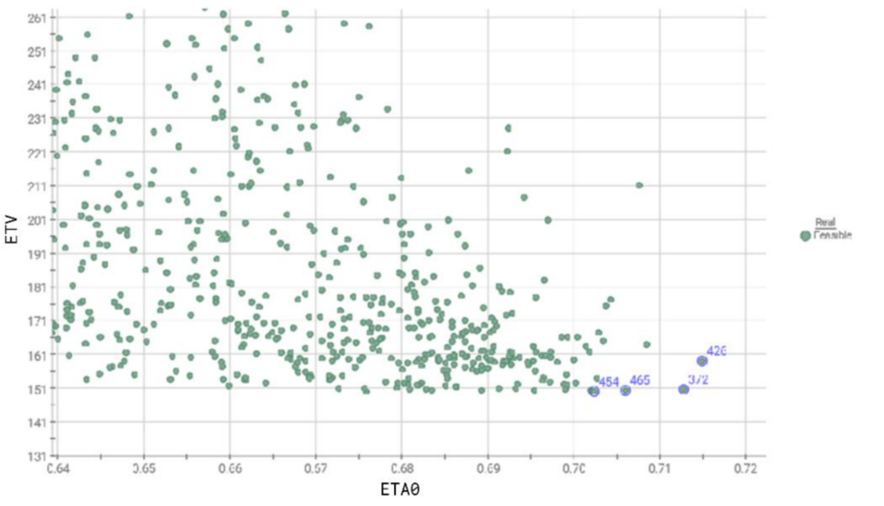

Figure 2: Pareto Front of the numerical optimisation

This optimisation was prepared as a multi-objective problem, where the objective functions were the following:

- Maximise the open water efficiency
- Reduce to the minimum first harmonic pressure pulses
- Minimise the tip vortex strength radiated noise, reducing the ETV

The following constraints were considered:

- Avoid cavitation on the blade surface (pressure higher than the corresponding vapour pressure)
- Match the margin against inception of pressure side cavitation.
- Pressure pulses lower than 0.3 kPa

The Pareto Front shown in Figure 2 was analysed, and, over few designs, a final refinement was applied to prepare the design for the manufacturing.

5. URN calculation

Once a preliminary propeller was optimised, a more accurate URN numerical estimation tool was required to estimate the propeller radiated noise more accurately.

As the underwater sound is strongly dependent on Mach Number, the model scale (obtained in Froude similarity) noise prediction is not accurate and should not be replicated numerically.

Fincantieri developed two Computational Fluid Dynamics (CFD) procedures to address the noise emitted by propellers and compare the results to full scale measurements. They are based on Detached Eddy Simulations (DES):

- A full-scale simulation of propeller behind hull without free surface in non cavitating condition. This is to simulate the silent class condition at low speed where no cavitation is present.
- A full-scale propeller simulation in the condition corresponding to the maximum KT in wake during the rotation in cavitating condition with cavitating tip vortex. This is used to simulate the transient class condition at higher service speed at about 80 % MCR.

5.1. Numerical Simulation: Propeller behind hull without free surface in non cavitating condition

This is a simplified simulation tool, which provides reliable results within the restricted time frame of the production process. It features the hull below the waterline, with no degrees of freedom, nor free surface, and with the propeller running (with a rigid body motion model) in the actual full-scale wake. Despite the simplifications, this tool provides good predictions, compared to full-scale results, and it allows an accurate comparison of different propeller geometries, in terms of radiated noise.

The simulation is an unsteady scale resolved DES calculation. After solving the turbulence and pressure fluctuation, with all the noise sources in the flow, the acoustic propagation calculation is performed by means of the Ffowcs Williams Hawkings [6] analogy. Instead of a permeable surface, the volume integration is performed in a portion of the domain which includes the hull, the propeller and wake behind it. To calculate the underwater pressure levels Lp, virtual hydrophones are placed in the same locations as during the URN sea trial tests.

Figure 3 shows the computational domain. The inlet is treated as a velocity inlet ($v=V_s$), the outlet as a pressure outlet ($p=p_0$), the ship hull as a no-slip wall, while the other boundaries are treated as slip walls; finally, a symmetry plane divides the computational domain at the ship's centreline.

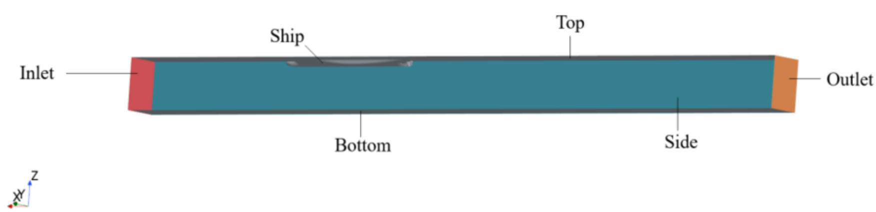

Figure 3: Computational domain

To couple the static domain with the rotating domain of the propeller, an interface was created. The mesh in the two domains, static and rotating, is different: a trimmed type for the first and a polyhedric for the latter. For the two domains, the total number of cells are 58'826'630 (15'935'819 for the rotating region and 42'890'811 for the static region) with a mean y+ value of 150 on the overall domain.

5.2. Numerical Simulation: Propeller with forced wake in cavitating condition

The second approach is employed to simulate the cavitating tip vortex and calculate its radiated noise. A full-scale DES simulation with the whole rotating propeller in wake and a cavitating tip vortex is often too computationally expensive and cannot be performed within a commercial project. Therefore, a simplified approach was developed. A single blade in a helicoidal periodic domain, with a periodicity equal to the number of blades, is tested with a constant inflow speed, corresponding to the lowest wake that the propeller can encounter during its rotation. This condition reproduces the maximum thrust coefficient (KT) and consequently the thickest tip vortex. With this procedure, the worst possible condition for the cavitating tip vortex is reproduced, and the noise radiation coming from its cavitation can be calculated. This approach is particularly useful to compare different propeller designs and select the most silent, based on the noise radiation generating from the tip vortex, which is the only type of cavitation observed on Fincantieri propellers in full scale and at full speed.

The cavitation model of Sauer-Schnerr is employed in the simulation, while models for coalescence and breakup of the bubble are not present. Some tests were performed with the Rayleigh Plesset cavitation model to define more accurately the bubbles behaviour, but it requires particularly fine meshes and very low time steps. The Sauer-Schnerr cavitation model proved suitable when the observed cavitation is semi-steady as a stable tip vortex cavitation with constant thickness.

In order to capture the cavitating tip vortex, the mesh needed to be refined as much as possible, reaching over 170 Millions of cells. Figure 4 shows the cavitation vortex of the blade.

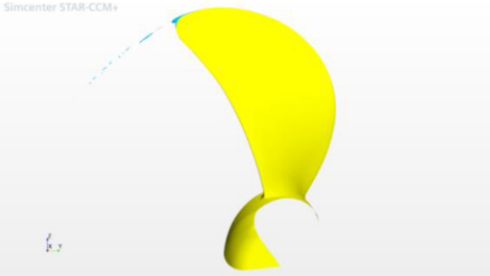

Figure 4: Tip vortex cavitation on propeller blade

6. Tank testing

Following the procedure described in the previous sections, a definitive propeller design was chosen, for a cruise ship with conventional shaft lines in the present case, and a fixed pitch propeller (FPP) model was built and tested in a depressurised towing tank. The aim of the experimental campaign was to validate the numerical simulations described in Section 5 and create a database to use as a benchmark for future projects.

6.1. Depressurised towing tank tests

The propeller was tested behind the relative ship model, in a self-propulsion configuration, scaled in accordance with Froude similarity. The model was tested according to Class Rules at 11 knots and at the contractual service speed.

Cavitation and pressure pulses tests were first carried out in order to verify the propeller load on the hull and to observe if any cavitation patterns were present. No cavitation was detected on the blades and the margin against the inception of pressure side cavitation was remarkably large.

Subsequently, URN tests were carried out, including background noise measurements.

To consider the scaling effect of tip vortex on URN, a correction was applied to the obtained results, in accordance with the procedure described in [7]. The measured data are scaled up to full scale and then corrected for the background noise and free surface effect on the whole frequency domain. Finally, the sound levels are normalised, at one meter, in 1/3 octave bands as prescribed by Class Notations (e.g., RINA Dolphin Class [3] and DNV Silent Class [2]). To obtain the source levels in full scale from model scale, corrections considering the Empirical Tip Vortex Model (ETV) [5] are applied. This model consists of several steps which consider the prediction of strength of the tip vortex, the size of the cavity, the pressure fluctuation and centre of frequency of the broadband spectral hump and the spectrum shape which comprises a high frequency (constant gradient flat spectrum) and a low frequency (broadband hump) part.

In both conditions, the propeller showed very little underwater noise radiation.

The propeller noise at low speed was difficult to distinguish from the background noise and resulted far below the cavitation inception limit, hence no ETV correction could be applied. The same propeller in transient condition at service speed showed very thin tip vortex cavitation. The ETV method could be applied in this case. The results are shown in Figure 5 and Figure 6 in Section 7, where they are compared to calculation and sea trial results.

7. Sea trials measurements

To verify that the vessel's compliancy with silent class rules, sea trials URN measurements need to be carried out and the far field technique is usually adopted. The underwater noise is therefore measured during dedicated speed runs in deep water, by means of three hydrophones located in the water, according to class requirements, at three different draughts, at a distance of the closed point of approach (CPA), usually between 150 and 250 m.

The raw noise signals are acquired in narrow band during each speed run, averaged and corrected for the background noise recorded before the vessel approaches the hydrophones. Calculations are made to get the noise source level at 1 m from the vessel, according to class rules, and reported in one third octave band. Figure 5 and Figure 6 show the URN performances of a super silent propeller of a Fincantieri cruise vessel, tested in silent mode at 11 knots and in transient mode at service speed, respectively. In both cases, it was observed that the noise level is almost 15 dB lower than required by the class limits on the whole frequency range. Figure 5 also compares the measured results to the limitations set by DNV for a research vessel. At low speed, the radiated sound level was almost not totally covered by background noise. This leads to the conclusion that the newly developed numerical procedure based on Ffwocs William-Hawkings equation and tank tests provide a good accuracy level in the prediction of the propeller URN at design stage.

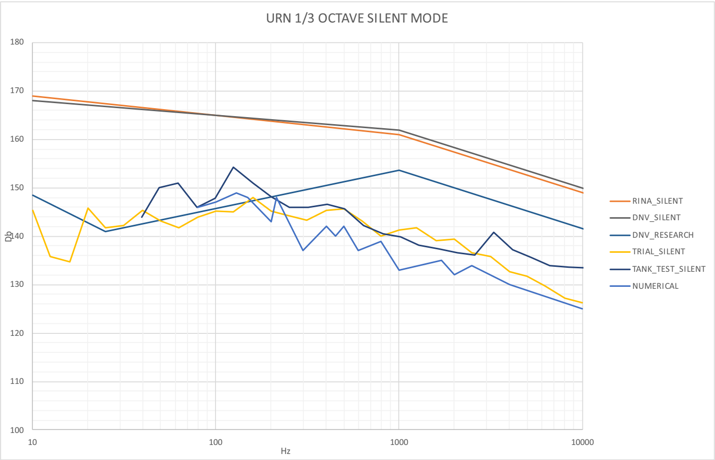

Figure 5: URN measurements and prediction at low speed in silent mode

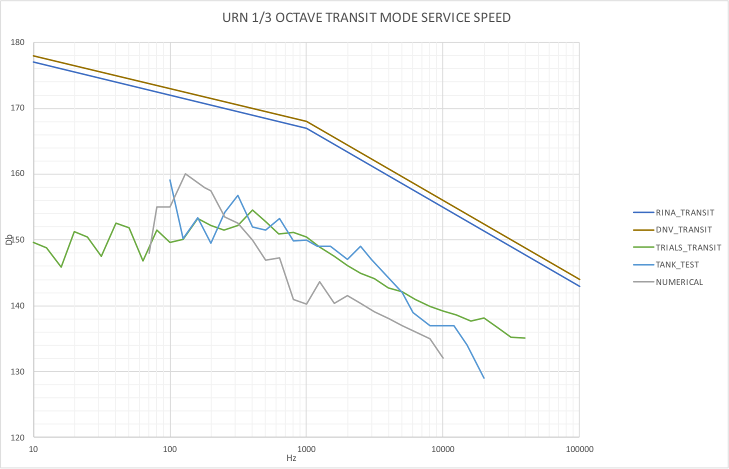

Figure 6: URN measurements and prediction at service speed in transient mode

8. Conclusions

With the aim of building cruise vessels that are more and more environmentally sustainable, not only in terms of CO2 emissions but also of URN, Fincantieri has developed numerical and experimental hydrodynamic design procedures to accurately predict and reduce the underwater noise emissions.

The authors addressed the challenging task of designing a silent propeller, preserving its hydrodynamic efficiency. The procedure developed by Fincantieri was described. The first step is the hull design: a forward-placed LCB is a fundamental factor to enhance the hull wake, which is the first necessary item to obtain a silent and efficient propeller. Secondly, 6-blade propellers proved as an optimal choice, since this allows the load reduction on each blade; this, combined with suitable pitch and camber distributions, which provide shock-free entrance and low bound circulation at propeller tip, enables the designer to avoid any types of cavitation on the blade surface.

A numerical approach was described, which permitted to numerically optimise the propeller geometry and test it by means of CFD calculations, before physical towing tank tests. Finally, the results were compared to sea trial measurements, showing full compliance with URN emissions Class Rules.

The sea trial results showed a very silent propeller, whose performance exceeds the trend for cruise vessels and is comparable to research vessels. This is far below the current limits set by statutory requirements and guidelines to preserve marine fauna, without compromising with the hydrodynamic efficiency and, consequently, emissions of carbon dioxide in the atmosphere.

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