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Cavitation tunnel tests for “The Princess Royal” model propeller behind a 2-Dimensional wake screen

**Giorgio Tani¹, Batuhan Aktas^{2, *}, Michele Viviani ¹, Naz Yilmaz², Fabiana Miglianti¹,
Marco Ferrando¹, Mehmet Atlar²**

¹Department of Electrical, Electronic, Telecommunication Engineering and Naval Architecture, (DITEN), University of Genova, Genova, Italy

**²Naval Architecture, Ocean & Marine Engineering, University of Strathclyde
Glasgow, UK**

Corresponding Author:

*Batuhan Aktas, batuhan.aktas@strath.ac.uk

Henry Dyer Building
100 Montrose Street
Naval Architecture, Ocean & Marine Engineering,
University of Strathclyde
Glasgow G4 0LZ, UK
Tel: +44 (0) 141 574 5342

Abstract:

Propeller noise, especially in the presence of cavitation, is usually the main contributor to the acoustic signature of ships. Due to this fact, considerable efforts have been devoted to the study of underwater radiated noise induced by propeller cavitation: firstly, for military reasons; more recently for other reasons relevant for merchant vessels, such as comfort on board and to mitigate the undesirable impact on marine fauna.

Different approaches are available for the study and prediction of the cavitation noise, including statistical and CFD based methods as well as a model test based approach in a cavitation tunnel or depressurised tank. Amongst these approaches, the model test based one is still the most reliable and commonly adopted method using cavitation tunnels. However, when the aim of the model tests is the prediction of noise radiated by a full-size ship, scale effects need to be analysed and taken into account to interpret the model scale data correctly to achieve reliable, and consistent predictions. Within this framework, each testing facility follows a procedure, which is developed through its own experience and possibly in semi-empirical nature, typically to manage these issues. Unfortunately, the definition and harmonisations of the ultimate standards for the noise tests and post-processing procedures of the propeller noise are still under developments as one of the current tasks of the ITTC Specialist Committee on Hydrodynamic Noise and other standardization institutes. This situation presents more uncertainty compared to other measurements for more established tests such as resistance and self-propulsion experiments, etc.

In this paper, model scale tests carried out at the University of Genova (UNIGE) cavitation tunnel on the model propeller of the Newcastle University research catamaran, "The Princess Royal", are presented behind a 2D wake screen to approximate the real ship condition. The details of the experimental setup, results and discussions on the comparative results of the cavitation and noise of this propeller with the full-scale measurements are presented to explore the issues of the scale effects. The paper, therefore, does not only examines the important issue of the scale effects but also provides invaluable new set of experimental data for the propeller of "The Princess Royal" which has been used as the benchmark propeller in the open literature including 28th ITTC Specialist Hydrodynamic noise committee.

Keywords: Model tests, Cavitation, Underwater radiated noise, scale effects, tip vortex noise.

Nomenclature:

μ	Dynamic fluid viscosity [kg/ms]	P_{atm}	Atmospheric pressure [Pa]
A_E	Expanded blade area [m ²]	P_v	Vapour Pressure [Pa]
A_E/A_o	Expanded Blade Area Ratio	Q	Torque [Nm]
A_o	Propeller disc area [m ²]	R	Radius [m]
$C_{0.7R}$	0.7 Radius chord length [m]	r	The distance between the acoustic centre of the noise source and hydrophone [m]
D	Diameter [m]	ρ	Fluid density [kg/m ³]
f	Frequency [Hz]	Re	Reynolds number
g	Gravitational acceleration [m/s ²]	r_{ref}	Reference distance (1m)
h	Shaft immersion [m]	SPL	Sound pressure level [dB]
J	Advance coefficient	T	Thrust [N]
K_P	Pressure coefficient	V	Speed [m/s]
K_Q	Torque coefficient	ν	Kinematic fluid viscosity [m ² /s]
K_T	Thrust coefficient	V_A	Advance speed [m/s]
L_{KP}	Pressure coefficient level [dB]	Z	Propeller blade Number
N	Rotational speed [RPM]	η_o	Propeller efficiency
n	Propeller revolution speed [rps]	σ_N	Rotational cavitation number
P	Pressure [Pa]	σ_V	Free stream cavitation number
P/D	Pitch ratio at 0.7R		

1 Introduction

First studies on cavitation noise date to WWII when its importance was mainly related to the detection of the submarines. Successively, these studies were associated with the military; until only recently, the noise problem of commercial shipping has also been addressed due to the increasing concerns on environmental issues and comfort on-board. During the last decade or so, theoretical models for the analysis of fluid flow around propellers, cavitation and consequent noise have been developing and attracting more attention but, due to the complexity of the real case studies, the experimental approach is still the most preferred choice, both for research and practical way of investigations for ship noise.

Due to the development of computational tools, with continuously increasing computational resources, the numerical approaches recently gained remarkable pace and importance in this field. In fact, nowadays, these approaches are considered to be reliable tools similar to those used for the analysis of ship resistance and powering performance analyses, e.g. (Gaggero et al., 2014; Gaggero & Villa, 2017; Bensow & Bark, 2010). Even the modelling of hydrodynamic and cavitation noise is currently addressed, with promising results, using CFD solvers like DES, LES and DNSS (Li et al., 2015; Lidtke et al., 2016; Lloyd et al., 2015; Keller et al., 2017). However, the numerical approaches using CFD still need further improvements, validations and verifications and hence their use is mainly limited to the research field because of the extreme computational demands of such simulations. Within this framework, the model test based approach is still considered to be the most reliable approach to predict the cavitation induced noise, e.g. (Bertschneider et al., 2014).

However, several aspects of the noise tests in model scale are still not completely understood, requiring further research and clarifications. For example, viscous scale effects simultaneously influence the propeller and its inflow characteristics, and hence the cavitation patterns on the propeller blade surfaces (Kuiper, 2012) as well as off the blades due to tip vortex cavitation and its trajectories (Mc Cormick 1962; Shen et al., 2009). In particular, the latter type cavitation is of great concern when the experiments are focused on a propeller characterised by limited cavitation, for which the correct prediction of the onset of the tip vortex cavitation and related noise become critical. Actually, for these applications, to correctly simulate tip vortex cavitation, the cavitation number identity should be abandoned by following other similarity laws, as explained by (Briancon et al., 2013), and also recommended by ITTC (7.5–02–01–05). However, in some cases, due to the presence of other phenomena, it is just not possible to achieve a consistent cavitation similarity between the model scale and full scale as explained by ITTC. Further scale effects, which may significantly alter the model scale results, are those related to the water quality and more specifically the nuclei content of the water (Cahine, 2004) and the effect of the noise propagation in a confined environment, e.g. (Tani et al., 2015a; Tani et al., 2015b).

Research institutes performing cavitation and noise tests are always involved in the development of suitable procedures to deal with the scaling issues mentioned above. However, their effectiveness may vary depending on the particular problem under study. Within this context, some examples of successful model scale measurements for the prediction of the ship

radiated noise are reported in the open literature from some large-scale dedicated facilities, e.g. (Bark, 1985; Hallander & Johansson, 2015; Bosschers et al., 2013, Seol et al., 2015). These facilities take the advantage of their favourably larger size and hence use full-models. Although the prediction task can be addressed at better in those large and dedicated facilities, some remarkable results can also be achieved in medium to small size facilities, where compromised truncated models with wake screens or purely 2D wake screens are used. Some examples of these studies are reported for example in (Atlar et al., 2001, Aktas et al., 2016, Tani et al., 2016, Traverso et al., 2016).

Due respect to the above-highlighted issues and taking into account the fact that each application case is associated with particular aspects, which may need further investigations, this paper explores the propeller cavitation and noise characteristics of the Newcastle University research catamaran, The Princess Royal (Atlar et al., 2013). The investigations are based on the model test data carried out in the medium to small size cavitation tunnel of the University of Genova (UNIGE) and the full-scale trials data available with this vessel. More specifically, the main objective of this paper is to analyse the cavitation and noise characteristics of the Princess Royal propeller which has become a benchmark propeller following the disclosure of invaluable full-scale trial and model-scale cavitation and noise data collected during the SONIC project, e.g. in (Aktas et al., 2016). The analyses are expected to shed further lights on the scale-effects related issues within the framework of a medium to small size facility practice as well as providing a new set of invaluable cavitation and noise data for this benchmark propeller.

The Princess Royal propeller is also used for the ongoing international Round Robin noise test campaign conducted by the members of the Noise Community of Practice of the Hydro-Testing Forum. Some of these test results have been presented by, e.g. (Lafeber & Lloyd, 2017; Hallander, 2017, Seol, 2017, Sakamoto et al., 2017) and also by the authors in (Tani et al., 2017b). However, this campaign involves the voluntarily simplified test case, where the propeller is subjected to uniform inflow with inclined shaft only instead of the real ship wake. In the present study, the cavitation tunnel tests are carried out in behind 2D wake conditions, and the results are compared with the sea trials data. The adopted setup and obtained results are discussed, trying to merge this new set of experimental results to the large set of experimental data available for this benchmark test case. Moreover, the test results are

discussed with particular attention given to cavitation stimulation, tip vortex noise and Reynolds number effects on the tip vortex inception.

In the remaining parts of this paper, Section 2 presents the details of the UNIGE cavitation tunnel and experimental set up as well as the details of the Princess Royal propeller, wake and operational conditions. Section 3 describes the details of the cavitation tests and the results analyses regarding to the cavitation observations including the comparisons with the full-scale observations. In Section 4, the model-scale noise measurements, analysis of the net propeller noise levels and comparisons with the full-scale noise measurements are presented. Finally, Section 5 includes the concluding remarks obtained from this study in terms of the cavitation, noise and associated scale effects.

2 Experimental Setup

Model tests presented in this study have been carried out at the UNIGE cavitation tunnel. The facility is a Kempf & Remmers closed water circuit tunnel which is shown in Figure 1. The tunnel features a square testing section of $0.57\text{ m} \times 0.57\text{ m}$, having a total length of 2m. The nozzle contraction ratio is 4.6:1, allowing to achieve a maximum speed of 8.5 m/s in the test section. The vertical distance between the horizontal ducts is 4.54 m, and the distance between the vertical duct is 8.15m.

Figure 1: UNIGE cavitation tunnel

The tunnel is equipped with a Kempf & Remmers H39 dynamometer which measures the propeller thrust, torque and rate of revolution. As usual, a mobile stroboscopic system allows visualising the cavitation development on propeller blades. Moreover, cavitation observation is also made using three Allied Vision Tech Marlin F145B2 Firewire Cameras, with a resolution of 1392 x 1040 pixels and a frame rate up to 10 fps.

Following the ITTC guidelines, the quality of the water in the tunnel is routinely checked during tests measuring the oxygen content through an ABB dissolved oxygen sensor model 8012/170, coupled with an ABB analyser model AX400. Nuclei content should be appropriately set to find the optimal compromise between cavitation stimulation and possible noise absorption problems due to free bubbles. The optimum nuclei content, approximated here by the dissolved oxygen level, varies depending on the operational conditions during tests, in particular, tunnel static pressure and cavitation pattern. As an example, conditions characterised by limited vacuum and close to cavitation inception require high oxygen content (typical values at UNIGE are about 60% or more). On the contrary, conditions obtained with high vacuum and large cavitation need considerably lower oxygen content (about 40%).

An experimental investigation on the effects of the oxygen content on cavitation and noise levels at UNIGE cavitation tunnel was presented in (Tani et al., 2017a) for round-robin tests on the same propeller, and in (Tani et al., 2017b) for another experimental campaign on a fast twin-screw vessel. Following the findings of these works and other previous experiences, tests were carried out considering two different oxygen contents, i.e. $DO_2 = 5.3 \text{ pp}$ (about 60%) for moderate cavitation conditions, and $DO_2 = 3.9 \text{ ppm}$ (about 40%) for developed cavitation conditions.

To simulate the propeller inflow, the nominal wake field has been reproduced at the UNIGE tunnel using 2D wire meshes placed in front of the propeller in accordance with the target axial wake data measured at the ITU Ata Nutku Towing tank (Korkut and Takinaci, 2013). This choice does not represent the optimum since the full-scale wake field should be preferred to reproduce the real propeller operating conditions correctly. However, it was decided to adopt the model scale nominal wake field to better compare results with tests previously carried out in other facilities. Also, the scaling factor of The Princess Royal's model propeller is relatively small (5:1) when compared with a typical conventional commercial vessel propeller

(e.g. $>20:1$). The adoption of full-scale wake field may represent a further step in the study of this interesting benchmark case for future activities.

For the wake simulations, the wire screen has been built iteratively, measuring the resulting flow field using a 2D-LDV device until a satisfactory agreement with the target wake has been achieved. The resulting axial wake field data in the cavitation tunnel is compared with the target wake as shown in Figure 2 by a polar graph; the missing values on the left side of the graph correspond to areas which were not accessible by the LDV beams in the UNIGE tunnel.

Figure 2: Cavitation tunnel wake field (left) vs towing tank wake field (right).

The three-dimensional flow behind the hull is also characterised by velocity components in the propeller plane which cannot be modelled using the wire meshes. However, these components are usually induced by a vertical upward velocity component and may be partially reproduced by the inclined propeller shaft. In the present campaign, it was decided to perform the tests both with and without shaft inclination, in line with the standard practice of the facility when dealing with cases where significant tangential flow components are expected.

According to the analysis of the tangential components measured in the towing tank (during wake surveying tests), an 8° shaft inclination was adopted to reproduce the tangential flow in the most critical blade positions, i.e. 90° and 270° having indicated 0° position is at the top dead centre.

Radiated noise measurements were conducted with three hydrophones, namely one Reson TC4013 and two Bruel & Kjaer type 8103. The hydrophones were coupled with the Bruel & Kjaer type 2635 charge amplifiers. The arrangement of the hydrophones set up is shown in

Figure 3. It is worth mentioning that the hydrophones and propeller configuration inside the tunnel is the same as adopted during the previously conducted round-robin campaign (Tani et al., 2017b).

Figure 3: UNIGE cavitation tunnel setup

One hydrophone (H1) was placed in a rudimentary acoustic chamber positioned on the observation window below the propeller. The other two hydrophones (H2 and H3), mounted on the streamlined supports, were positioned inside the test section, downstream of the propeller and outside the propeller slipstream. As it can be seen in Figure 3, hydrophone H2 was placed very close to the propeller disk. This layout allowed to improve the signal to noise ratio (SNR) for this hydrophone even in case of limited cavitation, and of course, as a drawback of such configuration, the near-field effects could be more significant for this sensor. On the other hand, this effect was practically negligible for the H1 hydrophone, as far as cavitation noise was concerned.

For the radiated noise measurements, records made of 2^{23} samples were acquired with a sampling frequency of 200 kHz, resulting in a records length of about 40 s.

2.1 Case study

The Princess Royal propeller is a five-bladed, fixed pitch propeller with the main characteristics listed in Table 1. A detailed description of propeller geometry is available in (Tani et al. 2017b).

Table 1: Propeller main characteristics and particulars

Full Scale Diameter [m]	0.75
Pitch Ratio at 0.7R	0.8475
Expanded Blade Area Ratio	1.057
Number of blades	5

Propeller operational conditions were defined according to the identity of the torque coefficient and cavitation number. Test conditions were defined as such to reproduce the conditions tested during sea trials, as reported in (Aktas et al., 2016). Cavitation tunnel were carried out only for those conditions for which cavitation was observed during the sea trials. Resulting conditions for the cavitation tunnel tests are summarised in **Table 2** where the cavitation number is calculated according to Equation 1.

$$\sigma_N = \frac{P_\infty + \rho gh - P_V}{0.5\rho N^2 D^2} \quad \text{Equation 1}$$

Table 2: Test conditions

Condition	Shaft RPM	Shaft rate [RPS]	STW (kn)	10K _Q	K _T	10K _Q (w)	K _T (w)	σ_N (nD)	Model shaft [RPS]
V1 / V1W	514	8.6	7.1	0.336	0.237	0.279	0.186	5.28	25
V2 / V2W	682	11.4	9.4	0.318	0.221	0.278	0.185	3.00	35
V3 / V3W	856	14.3	10.5	0.323	0.225	0.308	0.211	1.91	35
V4 / V4W	1141	19.0	15.1	0.318	0.221	0.282	0.188	1.07	35

As shown in Table 2, two values of the thrust coefficient (i.e. K_T and K_T (w)) are present, resulting from alternative definitions of the propeller operational conditions corresponding to the different engine settings (and ship speeds).

As mentioned, in the first case the torque coefficient identity was used; in particular, K_Q value adopted was obtained from the full-scale measurements, then the corresponding thrust coefficient was determined from the propeller open water (OW) characteristics. Following this approach, also propeller advance ratio may be derived from K_Q values; consequently, the ship-self propulsion parameters, in particular, the wake fraction may be found. The obtained values, ranging from (1 – w) = 0.72 for condition V1 to (1 – w) = 0.85 for condition V3, are

significantly lower than those predicted by model tests which are all close to 0.9. These values are also lower of the model scale nominal wake whose average value is 0.87.

Given the general research purposes of the present work, it was decided to test the propeller also for a set of alternative operational conditions defined differently. In particular, the thrust coefficients for the “W” conditions were derived from the propeller OW characteristics having computed the advance coefficient using the ship speed multiplied by the wake fraction values coming from the model tests. This second group of points differed only for what regards propeller thrust since the shaft rate (and thus the cavitation number) was kept constant.

In addition to the conditions mentioned above, further points were added to address possible scale effects on the inception of the tip vortex cavitation. In fact, at the condition of V1/V1W, limited tip vortex cavitation was observed in the full-scale while there was no cavitation present in the model scale. Hence further operational conditions were defined by scaling the cavitation number, according to Mc Cormick law (Mc Cormick, 1962), in an attempt to achieve the similarity of the cavitation number ratio (i.e. σ/σ_i). The additional points, named “V1 scaled” and “V1W scaled”, featured the same K_T values as V1 and V1W but with $\sigma_N = 3.7$. Shaft rate at cavitation tunnel for these conditions was set to 30 rps

3 Cavitation tests

Before the cavitation observations were to be conducted in correspondence to the ship operational conditions, the inception values of different cavitation phenomena were determined for a range of propeller thrust coefficient. The inception tests were carried out by direct visual observations, starting from a condition with no cavitation and lowering the cavitation number until the cavitation appeared on the majority of the blades. Tests were usually repeated to check the repeatability of the cavitation inception measurement and to increase the reliability of results.

The inception tests were carried out only for the level shaft condition without any shaft inclination. For what regards the inclined shaft condition, no significant differences were observed for the inception of the first phenomenon, i.e. tip vortex cavitation at 0° (top dead centre). The results of the inception tests for tip vortex cavitation, which are shown in Figure

4, presented the typical trend of this phenomenon, with the inception index increasing at higher propeller load, as expected. The reported values corresponded to the model scale inception indices, to derive the full-scale inception indices for which the Mc Cormick's scaling law had to be applied. This resulted in the full-scale shaft rate inception point of about 425 RPM. Slightly higher inception shaft rate, about 435 RPM, was obtained considering "W" conditions. Both of these values are slightly higher than what observed during sea trials. Actually, estimated cavitation inception in full scale was between 372 and 400 propeller RPM, as reported in (Turkmen et al., 2015). This discrepancy may be linked to typical issues of model scale tests including insufficient nuclei content, poor modelling of the wake field, cavitation stimulation, selected operational (hence propeller loading) conditions, etc.

Figure 4: Results of inception tests for tip vortex cavitation, model scale.

Within the framework of the scaling issues stated earlier, for the water quality effect, unfortunately, it was not possible to repeat the inception tests with varying nuclei content because of the time schedule limitations. Actually, the UNIGE facility is not equipped with such nuclei injection/control system, hence nuclei content in the tunnel can be adjusted only through time consuming gassing and degassing procedures. However, this aspect was deemed not responsible for the retarded cavitation anyway.

A significant difference concerning the full-scale conditions is the conduct of cavitation tunnel tests with the model-scale nominal wake field. As known from practice, the full-scale wake is different to the model-scale because of the well-known Reynolds number difference which results in different boundary layer development with more accelerated and hence contracted structure of boundary layer in the full-scale. However, the effect of such differences between the model and full-scale wake usually results in earlier inception for the models, on the contrary to that observed in the present case.

A further aspect, which may cause discrepancies concerning the real ship configuration, but also related with model tests in other facilities is the modelling approach of the wake field, e.g. as those reported in (Aktas et al., 2016; Lafeber & Bosschers, 2016). The use of the 2D wire screen approach, as applied in this study, is somewhat an approximate approach compared to the use of complete hull models or dummy hulls, even if the agreement between the wire screen wake and target wake were deemed pretty good for the present case. In particular, despite the nominal wake is very similar, this may not be the case when the effective wake would be considered. In fact, the propeller configuration on this ship is characterised by a rather low clearance between the propeller tip and the hull; in such case, it may happen that, due to the action of the propeller, larger portions of the hull boundary layer would be injected into the propeller disk than without the propeller. Evidence of the interaction between the propeller and hull boundary layer for The Princess Royal at full scale was the resulting presence of the propeller-hull vortex cavitation, as reported in (Turkmen et al., 2015; Sampson et al., 2015). However, this effect was not reproduced during the tests with the wire screen, even if the screen extension was arranged deliberately larger than the propeller disk diameter, because the hull boundary layer was simply not present.

One remedy for dealing with the viscous scale effect, which can result in retarded cavitation, is to add artificial roughness on the propeller blades to stimulate the earlier inception. However, this approach requires special expertise through extensive correlations between the model and full-scale cavitation observations and hence it is not a standard procedure that is used in UNIGE cavitation tunnel. It is therefore not explored in this study.

Finally, from what concerns the two alternative strategies adopted to define the appropriate propeller loading conditions for model tests; the first result seemed to confirm the better consistency of the torque similarity approach.

Cavitation observations at the tunnel were carried out with the three cameras positioned as follows:

- Cam0: Positioned on starboard, pointing towards the suction side of the blades passing at 0° position (TDC).
- Cam1: Positioned on portside, pointing toward the suction side of the blades passing at 180° position (BDC).
- Cam2: Positioned above the propeller, focusing the whole propeller suction side in the upper disc position.

No photograph of the pressure side of the propeller was presented in this paper since there was no cavitation observed on that side. Only Cam2 photographs are presented.

Considering the two alternative groups of propulsive points and the double shaft configurations, (with and without inclination) four model scale configurations (and hence test conditions) were available for each ship speed, allowing to discuss the effects of moderate variations in propeller loading and shaft inclination as described below.

Condition VI

This condition was presented by the cavitation number, which was close to that of the inception in model scale. However, during the cavitation observations and noise tests in this condition, no cavitation was observed, except for sporadic events. The same held for all possible variations of this condition, i.e. different thrust coefficient and shaft inclination. Thus, in line with usual practice in the similar cases, the scaled conditions only were considered for comparison with the full-scale.

Some views of the full-scale cavitation pattern at 900 RPM are shown in Figure 5, while Figure 6 displays the results for the corresponding condition at the cavitation tunnel and also comparing for different hypotheses considered for the propeller loadings and shaft inclination.

Figure 5: Sea trials cavitation observation, 900 engine RPM.

Figure 6: Model scale cavitation observations.

Full-scale cavitation was mainly characterised by the presence of leading-edge tip vortex. As visible in pictures (b), the leading-edge cavitation at 0° seemed to occur at two different spots: at inner radii, not very extended sheet cavitation was observed; this cavitation rolled up into a vortex structure at the outer end which developed in the chordwise direction; the second cavitation formation was observed at the blade tip, rolling up in the main tip vortex. The latter cavitation pattern seemed to be characterised by stronger cavitation dynamics, with some bursting, as visible in picture (a). Tip vortices featured with moderate extensions and persisted

in the propeller wake. They were characterised by a wavy pattern at the top dead centre position, as usually happens when propeller blade passes through a rather decelerated hull wake.

Finally, in picture (c) a propeller-hull vortex was visible. As reported by (Turkmen et al., 2015), this phenomenon started occasionally occurring around 1000 engine RPM; then its occurrence was more and more frequent moving to higher speed conditions.

Model scale cavitation was characterised mainly by the presence of leading-edge tip vortex correlating rather well with the full-scale cavitation pattern. However, the vortex was present only at 0° and partially in the slipstream at 90° , but less persistent than in full-scale. Also at 180° , where some wake disturbances were present, it was visible but smaller than at 0° .

Variations of the propeller load produced different cavitation extent, as expected, without altering its main feature or dynamics significantly. The effect of the shaft inclination was less evident: cavitation at 0° seemed slightly weaker with the inclined shaft, this aspect was partially amplified in photographs because of a small change in enlightenment this. Actually, according to direct visual inspections, differences between these two configurations were even lower. Phenomena at 90° were slightly more developed with the inclined shaft but also, in this case, the difference was almost negligible.

As a general comment, the model tests for the present case proved that the effect of the vertical flow on propeller cavitation was negligible if it compared to the effect of the non-uniform axial wake field. Even if the tested shaft inclination angle was remarkable, it did not produce a significant increase of suction side cavitation at 90° , neither an occurrence of pressure side cavitation at 270° .

For an overall well-developed cavitation comparison case, the cavitation pattern observed for condition V1 scaled (in particular without shaft inclination) seemed to be the most consistent. Thus the comments may be focused on this condition. Leading edge cavitation in model scale appeared around 0° while the blade entered the wake peak, then it extended towards the tip rolling up into a clear vortex which followed the leading edge and persisted in the wake as trailing vortex. Vortex diameter seemed comparable with the full-scale tip vortex diameter but it was less persistent, with a significantly lower extension in the slipstream. No vortex structures extending in the chordwise direction were observed, and the vortex at 0° seemed to

be characterised by a weaker appearance. Some waviness of the vortex was present but significantly less pronounced than in full-scale. Obviously, the propeller hull vortex was not reproduced with such configuration.

Conditions V2, V3, V4

Cavitation pattern observed for conditions corresponding to 1200, 1500 and 2000 engine RPM are reported in Figure 7, Figure 8 and Figure 9. For what regards model tests, only conditions V2, V3 and V4 without shaft inclination are considered since comments on shaft inclination and propeller load effects are similar to previous.

Figure 7: Sea trials cavitation observation, 1200 engine RPM (left) – vs – Model scale condition V2 (right).

Figure 8: Sea trials cavitation observation, 1500 engine RPM (left) – vs – Model scale condition V3 (right).

Figure 9: Sea trials cavitation observation, 2000 engine RPM (left) – vs – Model scale condition V4 (right).

At the 1200 engine RPM condition, thicker vortices were present, with some bubble cloud in the trailing vortex at 0° which may be related to burst phenomena. Sheet cavitation was slightly increased, and breaking up in two points shedding bubble and vortex structure in the chordwise direction. According to comments reported in (Turkmen et al., 2015) an intermittent hub vortex was present.

Model-scale cavitation featured the similar extensions, but sheet cavitation was limited to the outer blade sections ($r / R > 0.8$) while at full scale it was present also at inner radii. Vortices were increased and now trailing vortices persisted in the wake for more than one propeller diameter. Again, model scale cavitation seemed to be characterised by less violent cavity dynamics, without a significant burst of the vortex or break up of the sheet cavitation. Hub vortex cavitation was obviously not present in model scale because of the adopted configuration, as for the propeller hull vortex.

Moving on to the 1500 engine RPM condition, sheet cavitation development in full scale was significantly increased in thickness and chordwise extension. At the blade tip, the sheet cavitation rolled up into a thick and cloudy tip vortex. Thick trailing vortices were visible in the wake of the propeller. At the highest tested speed, sheet cavitation further increased, covering a significant portion of the blades. Large unsteadiness of the cavitation phenomena was observed, with breaking up and bursting. A definite tip vortex core was no more visible since the sheet cavity rolled up into a complex and cloudy structure and propeller slipstream was no more visible.

A similar trend was observed in the model tests: tip vortex and sheet cavitation increased their dimensions with strong interactions between the two phenomena. For V3 condition, sheet cavitation rolled up into a very thick vortex with a twisted shape. A more unsteady behaviour was observed for the tip cavitation at this condition. However there was not any clear breakup, and the cavitating core was still well defined.

The phenomena drastically changed in the V4 condition: the sheet cavity broken up at the tip in a cloudy and unstructured vortex while a second vortex was formed at the inner end of the sheet cavitation trailing edge. This second vortex presented a more defined cavitating core. Remarkable interactions were present between these two vortices, with the small vortex structure rolling around the larger one. This kind of dynamics is rather typical of propellers which experience large sheet cavitation close to the tip. This was also observed on the same propeller for one of the conditions tested during the round-robin campaign at UNIGE and ECT (Tani et al., 2017), but also in other facilities (Lafeber & Lloyd, 2017; Hallander, 2017, Seol, 2017, Sakamoto et al., 2017).

In summary, a satisfactory agreement between the model tests and sea trials was observed for what regards the general appearance of cavitation. However, further remarks can be made as follows:

- Cavitation inception in model-scale seemed to be slightly delayed compared to the full-scale observation, even after implementing the Mc Cormick scaling.
- Tip vortex and sheet cavitation reproduced in model scale were similar to those observed on the ship but slightly less extended: in particular, the sheet cavitation featured a lower radial extension.
- Model scale cavitation was characterised by significantly less violent cavity dynamics than in full scale.
- Some of the phenomena present in full scale, i.e. propeller hull vortex and hub vortex, could not be modelled at the cavitation tunnel because of the intrinsic limits of the adopted setup.

Of course, these aspects would be expected to have some influence also on the noise measurements, as it will be discussed in the next section.

4 Noise measurements

The measurements and subsequent post-processing of the model propeller noise were carried out in accordance with the ITTC guidelines (7.5–02–01–05) for model scale noise measurements.

The average Power Spectral Density, $G(f)$ in Pa^2/Hz , was computed from each sound pressure signal $p(t)$ using Welch's method of averaging modified spectrograms. The Sound Pressure Power Spectral Density Level, L_p , is then given by:

$$L_p(f) = 10 \log_{10} \left(\frac{G(f)}{p_{ref}^2} \right) \text{ (dB re } 1 \mu\text{Pa}^2/\text{Hz)} \quad \text{Equation 2}$$

where $p_{ref} = 1 \mu\text{Pa}$, ρ the water density, n the propeller revolution rate and D the propeller diameter.

The background noise was measured reproducing the same operational condition (in terms of the shaft revolutions, flow speed and vacuum) for the propeller with a dummy hub. The subtraction of the measured background noise from the total noise measured yield the net propeller noise in terms of the sound pressure levels, depending on the signal to noise ratio, as follows:

1. Signal to noise ratio higher than 10 dB:

No correction

2. Signal to noise ratio higher than 3 dB but lower than 10dB:

$$L_{PN} = 10 \log_{10} \left[10^{(L_{Ptot}/10)} - 10^{(L_{Pbg}/10)} \right] \quad \text{Equation 3}$$

3. Signal to noise ratio lower than 3 dB:

$$L_{PN} = L_{Ptot} - 3 \quad \text{Equation 4}$$

The net noise level calculated in the above manner were plotted against to the frequency. The curves plotted for the last case represented just the upper limits for the propeller radiated noise so they could not be used as an estimate of the propeller noise and these parts therefore were disregarded.

Net noise levels were scaled to the reference distance exploiting the cavitation tunnel transfer functions. These were measured for the three hydrophones using an underwater electronic transducer with known emitting characteristic, following the procedure described in (Tani et al., 2015a, 2015b). The transfer functions of the UNIGE tunnel were measured in the frequency range 100:100000 Hz, however, results below 300 Hz were less reliable because of the uncertainties in the measurement of the transducer transmitting voltage response in the free field; the results obtained are shown in Figure 10.

The transfer functions were measured for varying positions of the emitting source, generally placed in correspondence to the areas where larger cavitation was expected to occur. For the present case, the considered source positions were located on the propeller disk, at a radial distance from the shaft of about $0.6 R$ and distributed around the top dead centre, from -60° to 60° . The final transfer functions were obtained averaging the results of each source position. This procedure also allowed smoothening those local characteristics (humps and hollows) of transfer functions which were related to particular acoustic effects linked to a specific position of the transducer. This was beneficial since the raw results of the transfer function measurements were normally characterised by irregular shapes, such as spikes, hollows and large fluctuations, which did not correlate well with the propeller noise spectra. Actually the latter was usually smoother. These discrepancies between measured transfer functions and propeller noise spectra may be due to the difference nature of sources considered. Actually transfer functions were measured with a single, deterministic noise source, fixed in space, while cavitation could be considered as a distribution of uncorrelated sources moving through the flow.

Figure 10: UNIGE cavitation tunnel transfer functions.

As a first step in the analysis of results, the received levels of the total noise and background noise were compared to better identify the cavitation contribution to the total spectrum and distinguish it from the background noise component whose contribution was not always eliminated by the standard background noise correction as described above. This analysis is reported only for H3 hydrophone to demonstrate the procedure although possible differences in the results observed for the other hydrophones are discussed.

The comparison of the total and background noise is shown for different cavitation extent considering condition V1, and “V1 scaled” to analyse the signal to noise ratio with and without cavitation as shown in Figure 11 and Figure 12, respectively. Since the tests for such conditions were carried out with different shaft rate (25 and 30 RPS respectively), in these figures, the frequency range was represented as non-dimensional frequency using the blade passage frequency (BPF). The narrowband representation was adopted for identifying the different noise components better.

Focusing on the first condition, when the cavitation was not present, the total noise and background noise spectra were almost coincident because of the relatively high background noise levels in the UNIGE cavitation tunnel. It has to be born in mind that the background noise was even higher for the present test configuration because of the additional noise created by the wire wake screen arrangement.

All spectra are characterized by a significant amount of tones at mid frequencies. The tone at 4.2 BPF corresponds to the dynamometer bevel gear noise. Moving to higher frequencies, the

total noise is slightly higher than the background noise up to about 80 BPF. This difference with background noise is likely due to the higher noise produced by the whole dynamometer shaft line when the propeller is present, thus producing a different loading. However, also the propeller non-cavitating noise may contribute, especially from 30 to 80 BPF.

It is interesting to observe a narrow peak in the spectrum around 730 Hz, i.e. about 6 BPF for V1 (Figure 11), 5 BPF for V1 scaled (Figure 12). These peaks, mainly detectable in H3 spectra, are related to the vibration of the support of H3 hydrophone. Unfortunately, the magnitude of this component is usually higher when the propeller is present, and even higher if the propeller is cavitating. As a consequence, the background noise correction does not allow to eliminate it. Anyway, this component is significantly less intense in spectra from other hydrophones.

Figure 11: Condition V1, total noise vs background noise for hydrophone H3.

Passing to condition V1 scaled (Figure 12), the effect of cavitation is evident, with the total noise significantly higher than the background noise from about 4 BPF to the highest frequency. Some effects of background noise components on the total noise are still visible at 5 BPF, because of the already described hydrophone support vibration, and around 20 BPF where some tones, likely to be related to the mechanical noise, are visible. All the remaining part of the continuous spectrum represents the cavitation noise and may be used with the aim of full-scale noise prediction.

Figure 12: Condition V1, total noise vs background noise for hydrophone H3.

The extrapolations to the full-scale conditions are conducted by using Equation 5 and Equation 6 following the ITTC procedures.

$$\frac{f_s}{f_m} = \left(\frac{n_s}{n_m} \right) \sqrt{\frac{\sigma_s}{\sigma_m}} \quad \text{Equation 5}$$

$$SPL_s = SPL_m + 20 \log_{10} \left[\left(\frac{\sigma_s}{\sigma_m} \right)^w \left(\frac{r_m}{r_s} \right)^x \left(\frac{n_s D_s}{n_m D_m} \right)^y \left(\frac{D_s}{D_m} \right)^z \right] \quad \text{Equation 6}$$

where; subscripts “m” and “s” represent model scale and ship scale values of the corresponding parameter respectively. According to the UNIGE experience, the exponents (w,x,y,z) adopted are those corresponding to the “low frequency” scaling as reported in the ITTC guidelines. These are $w=0.75$, $x=1$, $y=1.5$, $z=1.5$ for the constant bandwidth spectra and $w=1$, $x=1$, $y=2$, $z=1$ for the proportional bandwidth, respectively.

It is worth mentioning that, for this case, the adoption of the other set of exponents leads to very similar results with slightly lower levels: for example; utilising the high-frequency exponent for the scaling of noise gives a 2.68 dB lower level in the case of the maximum speed condition. Differences between the two formulations are even lower for the other conditions.

The results of the noise predictions based on the cavitation tunnel tests are compared with the underwater radiated noise measurements conducted by the FP7-SONIC project full-scale trials campaign, Aktas et al (2016), as shown in Figure 13 through Figure 16. In these figures, the

extrapolated propeller noise measurements are compared with the full-scale noise measurements for the two propeller loading conditions (i.e. Vscaled and VWscaled) and two shaft inclination arrangements (i.e. $\beta = 0^\circ$ and 8°).

Figure 13 Comparisons of full-scale noise measurements and UNIGE Cavitation Tunnel predictions for V1 including Torque and Thrust identity methods and With the effect of shaft inclination

Figure 14 Comparisons of full-scale noise measurements and UNIGE Cavitation Tunnel predictions for V2 including Torque and Thrust identity methods and With the effect of shaft inclination

Figure 15 Comparisons of full-scale noise measurements and UNIGE Cavitation Tunnel predictions for V3 including Torque and Thrust identity methods and With the effect of shaft inclination

Figure 16 Comparisons of full-scale noise measurements and UNIGE Cavitation Tunnel predictions for V4 including Torque and Thrust identity methods and With the effect of shaft inclination

In discussing the results presented in Figure 13 to 16, the first comments are dedicated to the effects of shaft inclination and thrust coefficient. As shown in these figures, the noise levels measured with the 8° shaft inclination are generally lower than those measured with no inclination, even if the differences are generally limited, and the spectra present similar characteristics. This is in good agreement with the observed cavitation patterns. In fact, the cavitation dynamics induced by the non-uniform axial wake field are dominant concerning those caused by the tangential flow, even considering the high inclination angle adopted for these tests. As a consequence, the observed reduction in cavitation occurring at the 0° position has the main effect on slightly reduced radiated noise levels. Moreover, two different sets of propulsive points, resulting from different interpretation of ship propulsive data, have been considered for cavitation tunnel tests.

Thrust coefficient variations are significant (about 20% on average), and consequently, significant variations of the cavitation pattern and noise levels are observed. Suction side sheet cavitation and tip vortex cavitation are significantly reduced passing from conditions with a higher load (V_x conditions) to those with decreased load (V_{xW} conditions). Accordingly, also the noise spectra are generally characterised by lower levels for the V_{xW} conditions. This trend is reversed only for the conditions corresponding to 2000 engine RPM. In this case, the cavitation pattern persists to be in the form of very large sheet cavitation combined with the occurrence of double vortex cavitation with frequently bursting events.

As already noticed the vortex core at 0° (i.e. TDC), where it should reach its maximum extension, is partially destroyed. Hence the noise radiation due to vortex pulsation becomes less efficient. Since the vortex pulsation is the main mechanism responsible for the low-frequency peak in the spectrum this behaviour results in a possible reduction of the maximum levels of the peak in the spectrum. This cavity dynamic is present both for condition V4 and V4W, but it is more intense for the former, because of the higher propeller load, and hence resulting in lower noise levels for condition V4 than condition V4W.

As an overall summary of the comparative spectral analyses, it can be stated that in all cases the main spectra characteristics are always similar, indicating that the different hypotheses considered and setups adopted do not alter the cavitation behaviour of the propeller drastically and consequently the resultant noise.

By comparing the main features of the noise spectra obtained from the model tests and the full-scale trials, significant differences are present. Generally, the model scale spectra feature a narrow peak at the medium to low range frequencies where the noise levels are in most cases higher than those measured in the full-scale. Also, such a peak is not present in the full-scale spectra, even if their maximum is usually at a similar frequency. At the range of medium to high frequencies, the trend is reversed as such: moving away from the peak, the levels of the model scale spectra decrease rapidly by about 20 dB while the full-scale spectra decrease with a smoother downslope. As a result, for the large part of the spectra at medium to high frequencies, the full-scale noise is higher than the model scale noise level by about 10 dB. Above 1 kHz, the model scale spectra decrease by about 20 dB per decade, except the local rise around 10 kHz. It has to be noted that such wavy pattern is related to the application of the transfer functions. Also, the full-scale spectra present an almost constant decay above 1 kHz, however the decay is slightly lower for full scale spectra.

In summary, the full-scale spectra are characterised by flatter shape than model scale spectra: the slope of the low and high frequency portions of the spectra are lower and no evident peaks are present, except those related to blade rate tone. Full scale broadband levels are generally higher than model scale ones, except for those frequencies at which the presence of the noise level peaks characterises the cavitation tunnel based spectra.

The spectral peak observed in the model scale is likely due to the tip vortex noise since the cavitating vortices are known to produce noise through pulsation around their characteristic frequency, as explained in details, e.g. (Bosschers, 2009). During the present campaign, the model scale noise spectra were all characterised by this shape when the cavitation was present. The appearance of the noise spectrum is not always in this form to confirm the presence of the tip vortex cavitation. The dominance of the peak is usually more prominent when the large and persistent vortices are present, meaning that the vortex core pulsation is the driving noise generation mechanism. Whereas, the peak may be less evident when significant bursting phenomena are present.

The above-described aspect was observed, as an example, during the cavitation tunnel tests conducted with a coastal tanker propeller at the UNIGE facility, as presented in (Rizzuto et al., 2014). In this work, two different wake screens were used, corresponding to two alternative predictions of the full-scale wake fields. Tip vortex cavitation was present in both cases,

however the corresponding measurements showed that lower peak and higher broadband levels were present for the case with more bursting cavitation. Within the similar context, the differences between the model scale and the full-scale noise spectra can be related to the different dynamic behaviours of the cavitation observed. In particular, it was observed that the full-scale cavitation was more unstable and bursting compared to what observed in the model scale.

For the sake of comparison between the model and full scale it is worth reminding that also other phenomena, like the hub vortex and the hull-propeller vortex, were observed during the sea trials and such cavitation patterns may produce significant noise.

However, the main outcome of the present work is probably that the cavitation dynamics have not been reproduced in an entirely satisfactory way in model scale tests, in particular for what regards sheet cavitation at 0° and general burst phenomena. This fact is in partial agreement with the results of the tests carried out in other facilities, see (Aktas et al., 2016; Lafeber & Bosschers, 2016). Even in these experimental works, which involved different levels of approximation for the actual conditions, the model scale cavitation was generally found less pronounced than those observed during the sea trials. The reasons for such discrepancies can be related to many aspects including, e.g. the deviation in the real propeller geometry, inconsistent definition of the operational conditions, significantly different full-scale hull wake field etc.

5 Concluding remarks

This paper presented and discussed the cavitation and noise tests on the model propeller of the research vessel, “The Princess Royal”, conducted in the cavitation tunnel of the University of Genova. The paper also presented invaluable further experimental data for this largely studied benchmark test case as well as discussing the detailed analysis of the data to make contribution in the field of propeller cavitation and noise.

During these tests, the effect of the hull on the propeller was taken into account by simulation of the model scale nominal wake field obtained from the wake survey in a towing tank. The wake simulation in the tunnel was achieved using 2D wire-mesh type wake screens, as opposed to a full hull or dummy model, due to the limited dimensions of the Genova cavitation tunnel.

The tests also included the effects of different definitions of the propeller operational conditions, as well as the effect of the vertical flow induced by an inclined shaft.

The test results were analysed to investigate the cavitation inception, cavitation extensions and resultant radiated noise and extrapolated to full-scale to compare with the cavitation observations and underwater radiated noise data available from the sea trials for this vessel. The analyses of the test results and comparison with the full-scale measurements indicated the following conclusions in the cavitation and noise features of the benchmark propeller as well as the associated scaling effects:

Cavitation features

1. The cavitation inception predicted based on the model tests was slightly delayed compared to the full-scale measurements and predictions in other test facilities using the same propeller with different wake simulation set-up
2. Although the extent of the model scale sheet cavitation observed on the blades was less than that observed in the full-scale sea trials, even if from a qualitative point of view, the agreement was still satisfactory.
3. The effect of the vertical velocity (cross flow) component induced on the propeller disk due to the inclined shaft is almost negligible for the present case. Whereas, the effect of the non-uniform axial wake field is dominant concerning the tangential flow.
4. Alternative definitions of the operational conditions resulted in less coverage of the suction side cavitation due to the reduced propeller load. However, the general features of the observed cavitation did not vary significantly.
5. In all operational cases, the model scale cavitation was characterised by a significantly more stable behaviour without remarkable collapses or bursting phenomena. This is in contrast to the cavitation observations made on the full scale.
6. A possible reason to explain the underprediction mentioned above of the model scale cavitation is the interaction between the propeller and the hull, which was not accurately modelled in these tests because of the 2D wake screens used. In its real configuration, due to the small clearance present between the propeller and the hull, a certain part of the hull boundary layer would be sucked into the propeller plane by the action of the propeller, hence causing a stronger deceleration of propeller inflow in the top dead centre position. A similar phenomenon can be reasonably reproduced only by using a full hull or dummy (truncated) hull model in the cavitation tunnel. Hence this could

partially explain the differences in cavitation patterns and dynamics between the present work and sea trials or with the tests in other facilities.

Noise features

7. The results of the noise tests correlate rather well with the results of the cavitation observations. The radiated noise levels based on the model tests are lower than the measured full-scale noise levels over majority part of the noise spectra. However, the maximum peak in the spectra is higher for the model test based predictions, hence reversing the general trend.
8. The reason for the above-finding is likely to be related to the cavitation dynamics: model scale spectra are characterised by a prominent peak caused by the vortex cavity pulsation, and moderate broadband levels, usually associated with the collapse and burst of the tip vortex cavities. This is in perfect agreement with the above-described behaviour of the cavitation feature while the higher broadband levels measured in the full-scale confirm, the more unstable dynamics of the full-scale cavitation.
9. In summary, discrepancies in noise measurements are most likely due to the different dynamic behaviour of cavitation between the model tests and the sea trials. Several reasons may contribute to these differences, ranging from the typical scale effects to the particular limitations of the facility used and adopted setup.
10. Cavitation tunnel tests demonstrated that even considering significant variations of the thrust coefficient, the global features of the propeller cavitation did not vary significantly (see remark 4) and consequently the radiated noise spectra also presented similar characteristics.
11. Furthermore, it has been shown that the tangential flow does not affect the propeller cavitation significantly (see remark 3) and hence the resultant radiated noise for the present case.

In summary, the propeller inflow in model scale may be the most important cause of the differences compared to the full-scale, having an impact not only on the cavitation extension but also on the dynamic behaviour of the cavitation. As stated above, the flow field reproduced at the UNIGE cavitation tunnel may suffer the lack of interaction between the propeller and hull boundary layer. Also, the simulation of the model scale nominal wake field may have caused further discrepancies with the full-scale observations and measurements. However, based on the comparisons, the full-scale cavitation behaves as if the wake was even more

decelerated than the wake measured in the towing tank, which is contrary to what typically happens due to the difference in Reynolds number in the model and full-scale. This phenomenon requires further investigations which is always relevant in cavitation model tests and may be of utmost importance in this particular case due to the rather unusual hull shape which involves a deep-V cross-section combined with a tunnel stern.

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