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Single screw ships radiated noise measurements in model and full scale

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ABSTRACT

In this work the problem of underwater radiated noise emitted by cavitating propellers is addressed, considering the case of single screw ships. To this aim, a series of experimental results obtained in model and full scale is presented. The analysis of results reported allows to discuss the effect of the surrounding ambient in model scale measurements and the importance of a correct representation of the ship wake. A comparison of model and full scale measurements is also reported.

Keywords

Cavitation, underwater radiated noise, model tests, scale effects

1 INTRODUCTION

The performances of marine propellers have constantly increased during time, due to more demanding requirements to the designer and the parallel development of more accurate design and analysis procedures. Design requirements are no more limited to the "usual" requests for high efficiency and avoidance of erosive cavitation, but a greater attention is given to the limitation of cavitation "side effects", such as pressure pulses and radiated noise. Stringent requirements in terms of these effects are mainly connected to "high added value ships" (passenger ships, mega yachts, oceanographic ships, naval ships, etc.). Nowadays, however, the radiated noise control is gaining more and more importance also for merchant ships, due to an increasing attention to environmental issues and in particular to the limitation of the shipping impact on marine fauna, as discussed in Andrè et al 2011.

As regards cavitation prediction, CFD computations may provide reliable results in terms of cavitation extent, also in correspondence to considerably off-design conditions (Bertetta et al 2012), and of cavitation inception (Gaggero et al 2014b). However, a numerical prediction of radiated noise, especially considering the broadband range, is still problematic and based in many cases on semiempirical approaches (Bosschers 2009, Ræstad 1996). Despite many authors dealt with radiated noise during years, relating it to different cavitating phenomena (Blake and Sevik 1982, Blake 1984, Sharma et al 1990), this topic still presents a considerable lack of experimental data, which are of utmost importance for the validation of numerical models. This in many cases is due to the confidential nature of the problem of noise radiation from ships.

Experimental measurements, however, present many open questions, too, such as those related to scale effects; in particular, a correct representation of full scale ship wake field is very important, as discussed in ITTC 2001; moreover, it is well known that the influence of Reynolds number on cavitation is important, influencing for example, as reported in McCormick 1962, tip vortex inception and strength, which may be different from model to full scale at equal cavitation number.

This aspect may be relevant especially when conditions near to inception are considered, resulting in very different cavitation extensions in model and in full scale.

Apart scale effects, another problem related to radiated noise measurement consists in the evaluation of the effect of the surroundings on measured noise, as reported for example in Blake and Sevik 1982. This effect is relevant when measurements are carried out in confined spaces characterized by small dimensions compared with the sound wave lengths of interest, as it happens in model scale tests. This may turn out to be very important for low-medium size facilities, while larger facilities are less prone to this problem, which, however, is always present, at least in the lower frequency range.

In the present work, results of a series of measurement campaigns recently carried out at the cavitation tunnel of Genoa University, partly in the context of the European Project AQUO, are presented (AQUO 2012). Different aspects are covered in the study, such as the influence of ship wake on cavitation behavior and related radiated noise and the influence of the confined environment on the measurements. To deal with the latter problem, in particular, tunnel transfer functions for the specific test configuration were experimentally evaluated, following the procedure presented in Tani et al 2015. Results obtained in model scale have been compared to full scale measurements performed in the AQUO project, allowing to consider the scale-related issues, too.

2 OVERVIEW OF ACTIVITIES IN AQUO PROJECT

As mentioned in the previous section, part of this work has been carried out in the context of the European Project AQUO. Within the project, among other activities, a specific work package (namely WP2) is devoted to the characterization of the cavitating propeller as a noise source, both numerically and experimentally. In particular, two single screw ships are considered as test cases, i.e. a research vessel and a coastal tanker. Further activities, carried out in AQUO WP3, are then devoted to full scale measurements, in order to provide additional data for the validation of numerical tools and to allow for comparisons between model and full scale measurements.

The numerical activities, were carried out adopting different techniques, ranging from the more usual BEM and RANS approaches to the more complex (and more time consuming) LES and DES techniques. Numerical activities have been focused on different aspects related to the numerical prediction of propeller functioning, including at first numerical resistance tests and wake prediction and then computations of propeller behaviour, including open water and behind hull conditions (self propulsion tests); numerical predictions have been carried out in cavitating and non cavitating conditions, both in model scale and in full scale; some examples of the numerical results are reported in Gaggero et al 2014a.

Results from these numerical studies may provide useful data on the behaviour of the cavitating propeller, which is in many cases the most important noise source of the ship. In order to obtain far field radiated noise predictions, then, the above mentioned numerical results may be coupled to different techniques, such as the Ffowcs-Williams-Hawkings acoustic analogy (Testa et al 2008).

Notwithstanding the significant improvements of the numerical predictions capability, the correct modeling of propeller cavitation and (especially) noise generation by the sole numerical activities is still complex, in particular when dealing with broad band noise components. Due to this, experimental activities still represent a fundamental tool for propeller radiated noise prediction and, more in general, for a deep analysis of the problem. As mentioned, both model scale and full scale experimental campaigns have been carried out on two single screw ships. In particular, model scale activities were carried out by three institutes: the Coastal Tanker (Propeller 1) has been tested at SSPA towing tank and large cavitation tunnel and at UNIGE cavitation tunnel, while the Research Vessel (Propeller 2) at CEHIPAR towing tank and cavitation tunnel and at UNIGE cavitation tunnel.

The activities carried out included resistance, self propulsion and wake measurements at towing tank and cavitation tests in the different cavitation tunnels, including obviously radiated noise and pressure pulses measurements.

In particular, flow measurements behind the hull were carried out in model scale, being the wake one of the most important aspects involved in propeller cavitation and still a matter of discussion due to scale effects related to the large Reynolds number differences with respect to the ship. Moreover, measurements of propeller induced flow in stationary (i.e. open water condition) and non stationary (i.e. behind hull) conditions have been carried out by UNIGE and CEHIPAR respectively.

For what regards cavitation tunnel tests, the three considered facilities represent different sizes of industrial cavitation tunnels, large (SSPA), medium (CEHIPAR) and small (UNIGE) size. As a consequence, comparisons between results allowed also to investigate the influence of different testing setup and procedures on cavitation tunnel tests.

In particular, both CEHIPAR and UNIGE cavitation tunnel experiments have been carried out reproducing ship wake by means of wire screens and schematizing the aft part of the hull with a flat plate at a distance equal to propeller-hull clearance. In addition, in both facilities two different wake field were studied, allowing for an analysis of the influence of the wake field representation. CEHIPAR tests were carried out reproducing the model scale nominal wake field measured during wake surveys and the full scale nominal wake field computed by means of direct RANS simulations. In UNIGE experiments on both propellers only the full scale nominal wake field was considered, but for the coastal tanker propeller the full scale wake has been computed with two different approaches, a direct RANS simulation and the Sasajima wake contraction method (Sasajima and Tanaka 1966).

SSPA cavitation tests have been carried out, in accordance to the facility usual procedure, with the complete ship hull model inside the tunnel and carrying out the tests at high flow speed, compatibly with the measuring devices capabilities.

In addition to the analysis of the different model testing setup, an activity has been carried out in parallel to AQUO project at UNIGE cavitation tunnel in order to analyse the influence of the facility as an acoustical surrounding. In particular, the cavitation tunnel acoustic frequency response has been measured and the transfer functions obtained have been applied to different radiated noise measurements, allowing to investigate the influence of this aspect on radiated noise prediction by means of model scale experiments.

Full scale testing campaigns have been performed by SSPA and CTO for the coastal tanker and the research vessel respectively, including pressure pulses, hull vibration and underwater radiated noise measurements. In both cases, different functioning conditions have been considered, modifying ship speed by means of pitch setting. In the case of the coastal tanker, different ship displacements were also considered.

In present work, a selection of results obtained at UNIGE cavitation tunnel is presented. In particular, attention is devoted to two aspects, i.e. the importance of the confined environment in model scale and the effect of wake reproduction on noise measurements.

3 TEST CASES

The two considered test cases are a coastal tanker (Ship 1) and a research vessel (Ship 2), whose main characteristics are reported in the following Table 1. Both ships are single screw, equipped with a four bladed controllable pitch propeller (CPP); in Figures 1 and 2 a photograph of the two propeller models is reported.

Table 1: Ships / propeller main characteristics

Ship main characteristics		
	Ship 1	Ship 2
L_{BP} [m]	116.90	60.30
B [m]	18.00	10.50
T [m]	8.12	3.20
Δ [t]	13250	1150
V_{max} [kn]	abt. 15	abt. 13
Propeller main characteristics		
	Ship 1	Ship 2
Type	CPP	CPP
D [m]	4.80	2.26
$(P / D)_{0.7R}$	0.87	0.94
A_E / A_O	0.45	0.67
Z	4	4
Rotation	Right	Left

Figure 1: Coastal tanker propeller (scale 1:20)

Figure 2: Research vessel propeller (scale 1:10)

The main working conditions considered are summarized in the following Table 2.

Table 2: Ships functioning conditions.

Ship	V [kn]	Ship loading condition	Propeller $(P / D)_{0.7R}$
Ship 1	15	Design	0.87
	15	Ballast	0.87
	11	Design	0.87
	11	Ballast	0.87
	11	Design	0.521
	11	Ballast	0.521
Ship 2	12	Design	0.91
	11	Design	0.91
	7	Design	0.464

It has to be remarked that all conditions have been considered both in model and in full scale, apart the conditions at 11 kn for Ship 1 at design pitch, since the ship is operated at constant RPM, preventing the possibility of reducing speed varying propeller revolutions.

In the following sections main results will be summarized, focusing on the study of the two problems just described, the influence of hull wake on cavitation and radiated noise and the effect of noise propagation in model scale radiated noise measurements.

4 EXPERIMENTAL SETUP

Experiments were carried out at the Cavitation Tunnel of the Department of Electrical, Electronic, Telecommunication Engineering and Naval Architecture (DITEN) of the University of Genoa. The facility (Figure 3) is a Kempf & Remmers tunnel with closed water circuit, featuring a squared testing section of 0.57 m x 0.57 m, with a total length of 2 m.

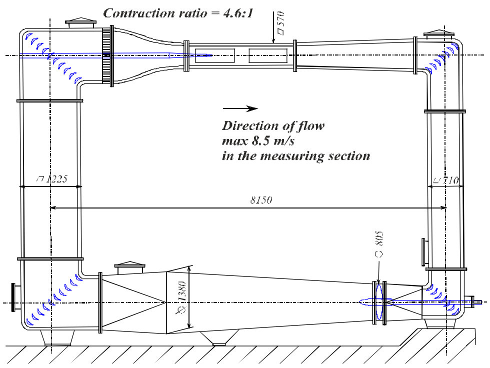

Figure 3: DITEN Cavitation Tunnel

The tunnel is equipped with a Kempf & Remmers H39 dynamometer and with instrumentation for non-intrusive measurement of velocity field, i.e. a Laser Doppler

Velocimetry (LDV). As recommended in ITTC 2008, during all tests oxygen content is constantly monitored by means of ABB dissolved oxygen sensor model 8012/170, coupled to an ABB analyzer AX400. Both campaigns were performed maintaining an oxygen content equal to about 40% of saturation value at atmospheric pressure.

In order to measure radiated noise, two hydrophones (namely a Bruel and Kjaer 8103 and a RESON TC4013) located in two rather different positions have been adopted; the first one protruding from a fin placed downstream of the propeller, inside the tunnel flow but outside the direct propeller slipstream (as visible in Figure 4 for Ship 1 case) and the second one located in an external tank (Figure 5), separated from tunnel flow by a plexiglass window having a thickness of 35 mm. The positions of the two hydrophones with respect to the propeller centre are reported in Figure 6 and Table 3.

In present work, for the sake of shortness results obtained with the internal hydrophone only will be presented since, after the application of the transfer function (see par. 5.1), the two measurements result rather similar.

Figure 4: Ship 1 (Coastal tanker) configuration

Figure 5: External hydrophone

For all the radiated noise measuring points, the corresponding background noise has been measured reproducing the same condition in terms of shaft revolutions, flow speed and depressurization and replacing the propeller with a dummy hub. Radiated noise measurements were carried out adopting a sampling frequency of 60kHz and acquiring 2^{21} samples for each record. Data records have been divided into 255 Von Hann windows with a 50% overlap. Each window has been analyzed by means of the FFT algorithm and the final spectrum has been obtained averaging the various window spectra, after elimination of the windows with considerably lower power, in case of intermittent phenomena.

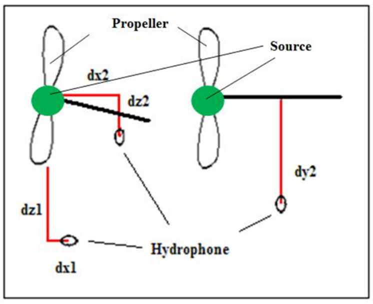

Figure 6: Hydrophones / source position (Tani et al 2015)

Table 3: Hydrophones and source relative distances

	H1	H2
dx [mm]	63	93
dy [mm]	0	147
dz [mm]	354	90.8

Radiated noise spectra are presented in terms of non-dimensional pressure coefficient K_P, defined as follows.

$$Kp = \frac{p}{\rho n^2 D^2}$$

$$L_{KP} = 20 Log_{10} \frac{K_p}{K_{P_{ref}}} \qquad (1)$$

where ρ =water density, n = shaft revolutions, D = propeller diameter and K_{Pref} = 10-6.

Net sound pressure levels are computed subtracting logarithmically the background noise from the total noise. The subtraction is considered reliable only if total noise exceeds background noise by more than 3dB, otherwise 3dB are simply subtracted to total noise.

Full scale spectra are obtained adopting following formulations for frequency (f) and for sound pressure power spectral density L_p:

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}$$

$$L_{ps} = L_{KPNm} + 20 \cdot \log_{10}\left(\frac{n_s^{1.5} D_s^3 \rho_s r_m}{D_m r_s}\right) \qquad (2)$$

Where r is the Propeller/Hydrophone relative distance; m and s subscripts refer to model and full scale respectively.

Radiated noise measurements were conducted at constant propeller revolution rate, namely 22.5 Hz for ship 1 and 25 Hz for ship 2.

As anticipated, the axial wake fields during all tests were simulated by means of wire screens suitably assembled and placed upstream the propeller; for what regards the tangential velocity components, two different strategies have been adopted for the coastal tanker and the research vessel. In the first case (Coastal tanker), tangential velocities, being mainly due to the vertical flow at stern, have been represented by means of a shaft inclination equal to about 8.5°, as visible in Figure 4. Moreover, two different wakes have been considered, both representing the full scale nominal wake, computed in two different ways; in particular, as reported in Rizzuto et al 2014, the ship wake directly evaluated by means of RANS calculations (figure 7) and the ship wake obtained scaling with the Sasajima approach the model scale nominal wake obtained from model tests (figure 8) have been reproduced.

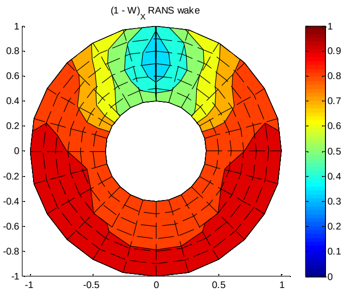

Figure 7: Ship 1 “RANS wake”

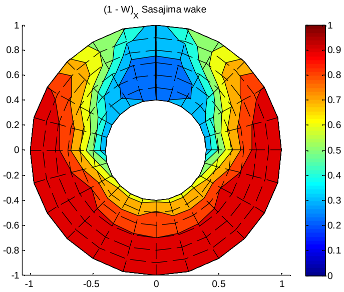

Figure 8: Ship 1 “Sasajima wake”

In the case of the Research vessel, on the contrary, an horizontal shaft configuration has been adopted, together with an “equivalent axial velocity”, in order to reproduce the blade angle of attack at different positions in the propeller disk. The resultant configuration may be observed in figure 9. In this case, only one ship wake (reported in Figure 10) has been considered, directly evaluated by means of RANS calculations.

Figure 9: Ship 2 (Research vessel) configuration

During the tests, also pressure pulses were measured by means of an ENTRAN differential pressure gauge EPX-N01-0.35B, mounted on a flat plate with faired leading and trailing edges (visible in Figures 4 and 6) placed over the propeller disk, maintaining the same clearance between hull and propeller of the real ship. Pressure pulses measurements are not included in present work, the presence of the plate is only mentioned to provide a full overview of the test setup.

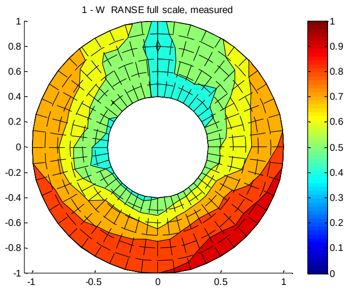

Figure 10: Ship 2 “RANS wake”

5 EXPERIMENTAL RESULTS

In present paragraph, a summary of the results obtained for the two test cases considered is reported. In particular, attention is given to the influence of the confined environment (par.5.1), considering both ships, and to the influence of the wake adopted (par.5.2), considering Ship 1 results.

5.1 Influence of noise propagation in model scale measurements

As already discussed, radiated noise model tests may be significantly affected by the surrounding (confined space) effects of the adopted facility, which is not open water. These effects may modify the resultant spectra, especially when tests are conducted in rather small facilities like the UNIGE cavitation tunnel.

In order to cope with this, a suitable procedure has been developed to measure the tunnel transfer functions and to modify the measured spectra before scaling them to full scale. The procedure is thoroughly described and discussed in Tani et al 2015 and is briefly summarized in the present paragraph.

At first, in order to obtain the transfer functions, the propeller is replaced by an underwater source, located in correspondence to the propeller shaft (centre of the propeller disk) and the two hydrophones have been located in the same positions adopted for the radiated noise measurements. The underwater source is a ITC 1001 transducer, which is a spherical broad band omnidirectional underwater transducer (see Figure 11). The radiating characteristics of the underwater source are at first measured in open sea during a dedicated campaign. The pre-determined signal is then transmitted by the transducer and acquired by the two hydrophones in the tunnel. The resultant spectra are used to obtain the frequency response of the tunnel.

The signal adopted is a pre-equalized sine sweep, and the signal recorded is treated by convolving it with a proper filter, in order to enhance the signal to noise ratio. The complete details of this procedure are not reported here for the sake of shortness and may be found in Tani et al 2015.

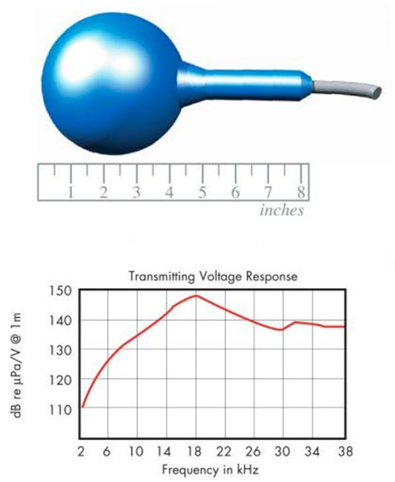

Figure 11: ITC 1001 underwater transducer

The two transfer functions obtained for H1 and H2 are reported in terms of 1/3 octave spectra in figure 12, showing a remarkable effect especially for the lower frequency range; in particular, it is clear that for H1 hydrophone (located in the external tank) the propagation effect is larger.

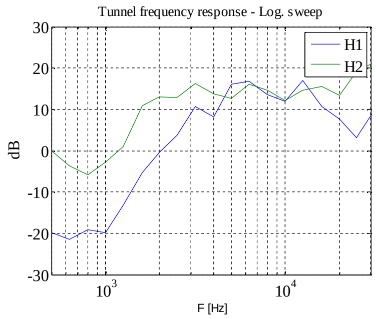

Figure 12: tunnel transfer functions (Tani et al 2015)

The effectiveness of the transfer functions has been tested comparing the spectra directly obtained by the two hydrophones and the spectra treated with the transfer functions themselves, considering a large number of functioning conditions of the two propellers. As an example, in Figures 13 and 14, results for a functioning point of Propeller 1 are reported, clearly showing the remarkable improvement of the results.

Since the results obtained in model scale for the two hydrophones were deemed satisfactory, the transfer function was applied to the spectra obtained for the two ships before scaling them to full scale. The comparison with the full scale measurements for the two ships is a further validation of the proposed procedure.

In the following Figures 15 and 16, two results obtained in correspondence to the design pitch and maximum speed for the two ships (namely the first condition for both ships in table 2) considered are reported. In particular, both transferred and not transferred spectra are reported, together with full scale trials results. It has to be remarked that results obtained with the internal hydrophone are considered in this case, since the differences between the two transferred spectra are rather limited; moreover, the transferred spectra are reported starting from 500 Hz since this is the lower limit for the transfer function; in the case of ship 1, results obtained in correspondence to the "RANS wake" are reported.

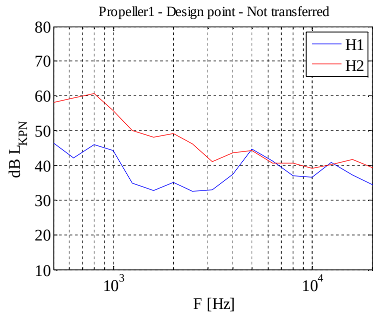

Figure 13: Prop.1 spectra not transferred (Tani et al 2015)

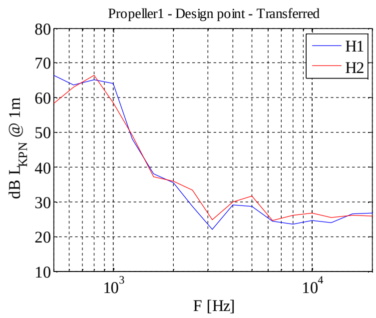

Figure 14: Prop.1 spectra transferred (Tani et al 2015)

As it can be seen, the application of the transfer functions considerably improve the quality of results in the case of Ship 1, reducing the gap between predictions from model scale tests and measurements in full scale, at least in the peak region.

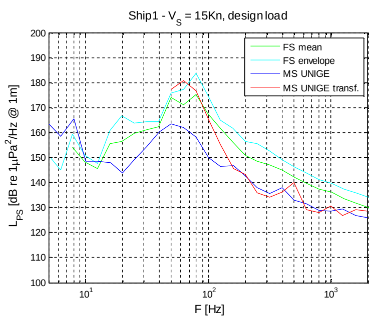

Figure 15: Prop.1 spectra – model vs full scale

In the case of Ship 2, on the contrary, the transfer function results in an overestimation of the spectrum peak. The various discrepancies may be attributed to different causes. As an example, the effect of the environment on the received noise levels, i.e. the evaluation of the transmission loss at the various frequencies, was numerically estimated using a wave number integration model named Scooter

(Porter, 1990), while, on the contrary, a direct measurement was made in the case of Ship 1.

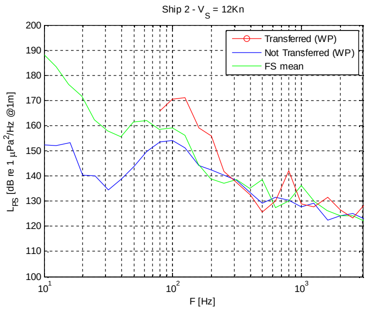

Figure 16: Prop.2 spectra – model vs full scale

Moreover, the wakes adopted for model tests may not be completely in line with full scale wake, since they were assumed from RANS calculations of nominal wake, which may represent a source of uncertainty; in addition to this, no modifications to account for the effective wake were introduced; this is implicitly considered when the hull model is present, like in large scale facilities, however it may be different when a wake screen is adopted. Finally, the limits of the adopted cavitation tunnel may have affected the results. Notwithstanding this, it is deemed that the procedure adopted has already provided promising results, which have to be further verified by means of other activities, considering other test cases and considering also larger scale facilities.

5.2 Influence of propeller inflow on cavitation and radiated noise

As discussed in the previous paragraph, one of the possible causes of uncertainty in radiated noise measurements is represented by the correct representation of the ship wake in full scale during cavitation tests. In order to (at least partially) deal with this issue, tests for Ship 1 have been carried out considering two rather different wakes, i.e. direct “RANS wake” (Wake 1) and “Sasajima wake” (Wake 2), as reported in section 4. As it can be seen, the direct numerical prediction results in a reduced peak at 0° position and in a lower overall deceleration if compared to the Sasajima approach. In particular, the mean wake fraction values are equal to 0.789 and 0.696 respectively for the two wakes, thus being considerably different.

Radiated noise measurements have been carried out at cavitation tunnel adopting the usual thrust identity approach (i.e. modifying propeller advance ratio until the K_T value predicted from self propulsion tests results is reached). As an example, the working points at design pitch corresponding to the lowest cavitation number tested (maximum speed and ballast load) are considered.

For the sake of clarity, photographs of cavitation phenomena at 0° are reported in Figure 17. As it can be seen, the propeller cavitating behaviors behind the two wakes look quite similar, with a well developed tip vortex at 0° connected with a sheet cavity extending from about 0.9-0.95R to the tip. The sheet cavity is larger for Wake 2, due to the larger (and more marked) wake peak at 0°; the tip vortex, on the contrary, is weaker for Wake 2 at different angular positions, since the thrust identity leads to less loaded blades outside the wake peak in order to compensate the higher thrust at 0°.

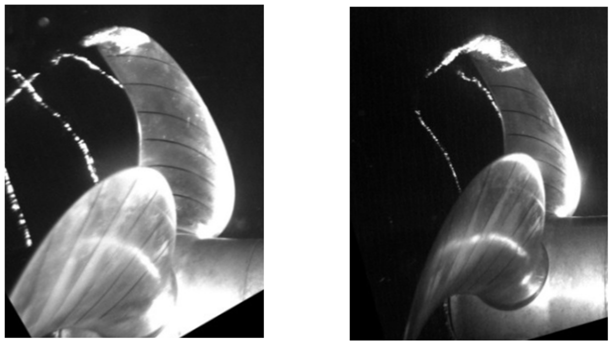

Figure 17. Cavitation extensions (Rizzuto et al 2014) (left: Wake 1 – right: wake 2)

The resultant radiated noise predictions are reported in Figure 18.

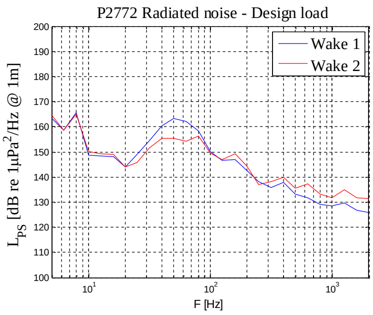

Figure 18: Prop.1 spectra – wake 1 vs wake 2

As it can be seen, measurements performed behind wake 2 show increased broad band noise. On the other hand, wake 1 causes higher noise levels at low frequencies, where noise emitted by the pulsating tip vortex is dominant. This may be ascribed to the characteristic dynamics of the tip vortex, which, in the case of wake 2, was characterized by larger random fluctuations and bursts, thus leading to a more spread spectrum. Moreover, in wake 2 the tip vortex is anticipated and stronger at 0° position, while it is postponed and considerably weaker in other positions, thus resulting in a less marked characteristic spectrum at lower frequencies.

Reasons for this result have to be further analysed, considering similar cases. Nevertheless, from this example it appears that the large difference in the two wakes results, as obvious, in two different spectra. The discrepancy between them, however, is lower than expected; this is probably related to the marked wake peak present in both cases, which leads to developed cavitation and to rather marked bursts of cavitating phenomena when moving outside the peak itself. As a consequence, in this case the nature of the spectrum is well captured adopting both the approaches for the full scale wake prediction.

6 CONCLUSIONS

In this work the problem of underwater radiated noise emitted by cavitating propellers has been addressed. A series of experimental results obtained in model and full scale for two single screw ships has presented, allowing to discuss the effect of the confined space in model scale measurements and the importance of the representation of ship wake.

The adopted transfer functions to model scale measurements appear to be effective, allowing to obtain a satisfactory agreement of measurements carried out with two hydrophones in very different positions in the cavitation tunnel. Moreover their adoption seem to improve the correspondence between model and full scale results at least in one of the cases considered, while the uncertainties of the second case do not allow to reach a clear conclusion.

Measurements in model scale with two different full scale wakes allow to provide a possible estimation of the uncertainty connected to wake representation; this appears to be present but less marked than expected, being the dominant characteristic (wake peak) simulated in both cases.

As a whole, the procedures adopted both to consider confined space effect in model scale and to predict full scale wake (with direct RANS approach) seem promising; further analyses are certainly needed in future to enlarge the database of data available, including certainly full scale measurements, which appear vital for a final validation of the adopted procedures.

7 ACKNOWLEDGEMENTS

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