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Round Robin Test on Radiated Noise of a Cavitating Propeller

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ABSTRACT

Mitigation of shipping noise is a topical issue in marine engineering because of the dramatic increase in the levels of anthropogenic underwater noise and its impact on marine life. In recent years, hydro-acoustic research has been very much focused on the development of reliable methods for predicting underwater radiated noise (URN) due to cavitation, which is known to be the dominant contribution to the overall radiated noise spectrum of ships above the cavitation inception threshold. Model-scale measurements are currently considered the most reliable approach to study URN problems in naval and marine engineering and are crucial for the verification and validation of numerical methods. However, their reliability is affected by several uncertainty sources for which suitable test procedures and post-processing techniques are needed.

As a means to better understand the accuracy and reliability of underwater radiated noise measurements, a round robin (RR) test programme for an open water propeller setup was organized within the Community-of-Practice "Noise" of the HydroTesting Forum, with the aim of comparing results among several institutes (i.e. University of Genova UNIGE, University of Strathclyde, NMRI, SSPA, KRISO, CNR-INM and MARIN). This paper reports an overview of the RR programme and compares the different approaches and results.

Keywords

Underwater Radiated Noise, Propeller Noise, Cavitation, Round Robin Tests.

1 INTRODUCTION

The substantial growth of the shipping traffic, with particular reference to tankers, bulk carriers and containerships (i.e. between 80% and 90% of international trade is transported by sea and this has increased more than four-fold since 1970) and the general increase in the size and speed of commercial ships has produced a significant growth in the volume and intensity of URN (Report on CISMaRT/Transport Canada Workshop on Ship Noise Mitigation Technologies for a Quieter Ocean). This has made its negative effects on several aspects of marine life particularly harmful, especially on marine mammals. Therefore, the need to reduce the noise levels, particularly in regions where there is close proximity between ships, and marine life, has also become more important (Hildebrand, 2009). One significant resulting initiative was the development of broad non-mandatory guidelines under the auspices of the International Maritime Organization (IMO), with the aim of reducing underwater radiated noise to levels that do not adversely affect the marine environment (IMO MEPC.1/Circ.833: Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life, 2014). It is likely that in the near-future local regulations concerning URN will come into force to protect wildlife in particularly sensitive areas. To this end, a major issue concerns the need to develop and validate reliable computational and experimental noise prediction and assessment tools to support the diagnostics and the cost-effective evaluation of the design with regard to URN, which is in perspective a key issue to ensure a ship's compliance with mandatory regulations.

While representing a promising approach for addressing the prediction of the noise footprint of ships and to support underwater noise mapping in critical areas, the adoption of numerical methods is still very challenging, particularly where cavitation dynamics are concerned, and the related effects on radiated noise (ITTC, 2014). This implies the need for further development and validation before numerical methods can be used reliably as a standard tool in design practice. On the other hand, model-scale tests are currently a more affordable alternative to numerical methods for the prediction of full-scale URN. Nevertheless, model scale tests are affected by several uncertainty sources that, in many cases, can significantly jeopardize their reliability. As an example, these involve the effects of the acoustical response of the facility and reverberation, which may cause the accuracy of URN prediction to deteriorate, especially in the low-frequency range (see e.g. Kuttruff, 2009; Briançon, 2013; Tani et al., 2015). Other uncertainty sources consist of i) the influence of facility background noise, ii) the water quality, iii) the determination of the loading conditions (i.e. advance coefficient or mean thrust coefficient, cavitation number), iv) the simulation of the correct cavitation extents and dynamics due to the influence of differences in the wake field, cavitation inception and gas content, v) the procedure adopted to scale measured noise spectra to full scale, vi) the influence of instrumentation, measurement procedures and setup. For an overview of measurement and scaling issues related to model scale noise tests and full scale predictions see e.g. (Lovik, 1981; Blake and Sevik, 1982; Bark, 1985).

In general, there is no universally adopted procedure for URN tests at model scale and each facility adopts its own method while similar methods for installation, test condition, data acquisition and scaling are used depending on the size and conditions of the facility.

This scenario has created the need for a research programme focused on assessing the accuracy and reliability of URN measurements at model scale and aimed at evaluating the impact of different experimental facilities and test procedures. To this end, the Community of Practice (CoP) "Noise" of the HydroTesting Forum (HTF, https://www.hydrotestingforum.org/), which followed from the HydroTesting Alliance (European Network of Excellence), has carried out a round robin (RR) test programme about the URN of a cavitating propeller. The RR test programme involves different propeller scale factors and facility types including small- and medium-scale cavitation tunnels, large-scale cavitation tunnels and large facilities such as a free-surface cavitation channel and a depressurized towing tank.

The present paper reports an overview of the round robin programme, including details of the facilities and experimental setups, data analysis methods and a comparative analysis of the results in terms of radiated noise levels and cavitation extension.

The paper is organized as follows. The description of the RR test programme is reported in Section 2 together with an overview of the test facilities and the experimental setups. The post-processing procedure employed for noise data is documented in Section 3. The results are discussed in Section 4, focusing on cavitation in sub-section 4.1, and noise in sub-section 4.2. Finally, conclusions are drawn in Section 5.

2 THE ROUND ROBIN TESTS CAMPAIGN

The test case for a round robin has to fulfil some important requirements. The availability of data on propeller geometry, preferably publishable, is crucial for the aims of the round robin test, whereas information on ship characteristics and sea trials results are important for its

Figure 1: One model scale propeller of The Princess Royal".

possible follow-up and implications. All these requirements are met by the propeller of the Research Vessel "The Princess Royale", shown in Figure 1.

This propeller has been the subject of a very large experimental campaign carried out at the Emerson Cavitation Tunnel (ECT) of the School of Marine Science and Technology at Newcastle University (Aktas et al. 2016a). Furthermore, several model-scale experiments on this propeller, (Lafeber and Bosschers 2016, Tani et al. 2019) and full-scale measurements (Dambra and Firenze 2015, Turkmen et al. 2017) have been carried out within the EU project SONIC (https://www.sonic-fp7.eu/) and other research activities.

Propeller cavitation noise is a complex subject and the results of a model-scale experiment are influenced by many scale effects and measurement issues. In order to focus on the comparison between different facilities, a simple open water configuration has been adopted, also including an inclined shaft configuration, to address non-stationary cavitation induced by the oblique propeller inflow.

Table 1: Propeller operational conditions for round robin tests.

Loading Condition	β [°]	J [-]	σ_V [-]
C1	0	0.4	13.9
C2			8.1
C3			4.5
C4		0.5	13.9
C5			8.1
C6			4.5
C7	5	0.4	13.9
C8			8.1
C9			4.5
C10		0.5	13.9
C11			8.1
C12			4.5

For both configurations (straight and inclined shaft angle), six operational conditions have been considered. These conditions, summarized in Table 1, have been defined as different combinations of advance ratio J and cavitation number σ_V, where:

$$J = \frac{V}{(nD)} \quad (1)$$

$$\sigma_V = \frac{P_0+\rho g h-P_V}{0.5\rho V^2} \quad (2)$$

where V is the forward speed, n and D are the rotation rate and the diameter of the propeller, ρ is the water density, g is the acceleration due to gravity, h is the water head, P_0 and P_V are the undisturbed pressure and vapour pressure. Whereas the propeller configurations have been selected aiming to study simplified test cases, it was decided to keep all possible sources of discrepancies that may occur within different institutions addressing the same experiment. These include important functioning parameters such as the flow rate and the propeller rotational speed, the employment of different propeller models with slightly varying sizes, and generally different experimental procedures, according to the characteristics and experiences of each participant.

As a consequence, results of the round robin tests are influenced by a variety of effects, which will be summarized hereafter considering the following categories:

- Facilities and main functioning parameters.
- Cavitation testing procedures.
- Water quality.
- Hydrophones configurations.
- Post processing.

Starting from the first point, the main characteristics of the facilities and experimental setups adopted in the whole campaign are summarized in Table 2.

As it can be seen, the combination of different propeller diameters and functioning parameters results in a rather large range of Reynolds number values, see equation (3), from a minimum of 1.11E+06 to a maximum equal to 2.32E+06.

$$Re_{0.7} = \frac{C_{0.7}\sqrt{V^2+(0.7\pi n D)^2}}{\nu} \quad (3)$$

These differences are also reflected in the special procedure adopted for cavitation testing. Some institutions adopt special treatments of the blades to stimulate the transition to turbulent flow. This is important for tests in the depressurized wave basin since the Reynolds number achieved in this facility is usually lower than that obtained in a cavitation tunnel. To mitigate this, MARIN applies strips of carborundum grains on the leading edges of the propeller blades. MARIN is not the only institution using special techniques to stimulate turbulent flow on the blades: SSPA, despite the large Reynolds number achieved, uses a special paint, which increases the surface roughness.

A further important aspect in cavitation testing is water quality. The amount and size of cavitation nuclei present in the water significantly influence cavitation development, starting from the inception of the first cavitation phenomena occurring on a model propeller, usually tip vortex cavitation, whose dependency on the amount of cavitation nuclei is well known (Kuiper 1981, Korkut 1999, Kamiriisa 2001). On the other hand, the amount of gas dissolved in the water may significantly influence bubble dynamics and in particular the intensity of bubble collapse. As a consequence, the noise produced by propeller cavitation may vary significantly, especially for near-inception conditions whereas the effects of the water quality are slightly reduced when considering conditions with developed cavitation.

Table 2: Summary of participants and main characteristics of facilities and experimental setups adopted.

Participant	Propeller model	Propeller diameter [mm]	Facility type and test section size [m] (LxBxT)	test conditions					
				β [deg]	J	V [m/s]	n [rps]	σ_V	$Re_{0.7}$ (J=0.4; J=0.5)
MARIN	MARIN	250	Depressurized Wave Basin 240x18x8	0°, 5°	0.4/0.5	1.7/2.1	according to J and U□	4.5 / 8.1 / 13.9	1.12E+06 1.11E+06
University of Genova	CNR-INM	220	cavitation tunnel 2x0.57x0.57	0°, 5°	0.4/0.5	according to J and n	35 / 30	4.5 / 8.1 / 13.9	1.78E+06 1.80E+06
SSPA	CNR-INM	220	cavitation tunnel 2.5x0.785 (circular)	0°, 5°	0.4/0.5	4	according to J and U□	4.5 / 8.1 / 13.9	2.31E+06 1.87E+06
University of Newcastle	UNEW	214	cavitation tunnel 3.1x1.219 x0.806	From -9° to + 9°, step 3°	From 0.4 to 0.75, step 0,05	4	according to J and U□	4.5 / 8.1 / 13.9	2.25E+06 1.81E+06
KRISO	KRISO	250	cavitation tunnel 12.5x2.8x1.8	0°, 5°	0.4/0.5	3.5/4.4	35	J=0.4 (7.0/8.1/13.3) J=0.5 (4.5/8.1/13.3)	2.3E+06 2.32E+06
NMRI	CNR-INM	220	cavitation tunnel 2.25x0.442 (circular)	0°, 5°	0.4/0.5	according to J and n	36.4 / 45.5	4.5 / 8.1 / 13.9	2.31E+06 1.87E+06
CNR-INM	CNR-INM	220	free surface cav. channel 10x3.6x2.25	0°, 5°	0.4/0.5	To be done	To be done	To be done	To be done

Finally, also noise propagation in the water is influenced by the amount of free bubbles suspended in the flow, which may cause noise absorption. The magnitude of this effect depends on the characteristics and equipment of the facility. Several techniques exist to assess the water quality (Billet et al. 2002). For the round robin test campaign all institutions involved adopted techniques based on the measurement of the quantity of gas dissolved in the water: most institutions measured the oxygen content while MARIN and SSPA measured the total gas content.

The water quality adopted for tests by the different institutions is summarized in the following:

- MARIN: Air content at 39% saturation: 10.7 ppm (kg); estimated subdivision in nitrogen and oxygen (other gases are neglected): N_2 (nitrogen): 6.7 ppm (kg), O_2 (oxygen): 4.1 ppm (kg).
- UNIGE: different oxygen levels have been adopted depending on the tunnel internal pressure and propeller cavitation: 6.2 ppm (kg) for loading conditions C4 and C10, 3.7 ppm (kg) for conditions C3, C6, C9 and C12; 5 ppm (kg) for the remaining conditions.
- SSPA: 20% total gas content.
- UNEW: oxygen between 3.7 and 4 ppm.
- KRISO: oxygen 6.3 ppm
- NMRI: oxygen between 3.7 and 4 ppm.

Different hydrophones configurations have been used in the round robin campaigns. Cavitation tunnels mainly rely on hydrophones mounted on streamlined supports directly inside the test section (UNIGE, SSPA, NMRI) and hydrophones placed in acoustic chambers of different sizes (a large anechoic chamber at KRISO, a small PMMA chamber at UNIGE, a small steel cylinder at UNEW). These chambers are filled with water at rest and placed on the surface of the test section, mostly close to the propeller position in the longitudinal direction.

A different configuration is instead used in the depressurized wave basin, where hydrophones are mounted on a mast raised from the tank bottom, with hydrophones positioned at 1.45 m from the free surface. Contrary to the other facilities, in this case the propeller and hydrophones are not both fixed in space; the propeller passes above the hydrophones similarly to the measurement of radiated noise of a real ship at sea.

The post-processing of noise data is subdivided into two steps: the processing needed to compute the Source Strength Levels (SL) or the Radiated Noise Levels (RNL) (ITTC, 2017), which may be slightly different for each facility, and the scaling laws applied to reduce all the data to a common reference condition for the sake of comparison. More details on the post-processing are given in the next paragraph.

Finally, it is worth mentioning that several additional investigations have been carried out by some of the involved institutions, such as tests at different shaft rates, varying oxygen content, tests with and without electrolysis, etc.

3 POST PROCESSING OF NOISE DATA

Noise signals have been acquired according to the standard procedure of each facility concerning the equipment used, the sampling frequency and duration of the acquisition.

Noise signals are processed in order to obtain noise spectra in both narrowband and one-third octave (OTO) band representation, each facility employing its own method to compute the power spectral density: mainly methods based on the Fast Fourier Transform (FFT) are used, but considering different window types, window length, overlaps, etc. One-third octave band spectra are obtained by means of both hardware and digital filters, or by integrating the power spectral density.

For both spectral representations, sound pressure levels (SPL) are defined as follows:

$$SPL = 10\log_{10}\left(\bar{p}_{rms}^2 / p_{ref}^2\right) \tag{4}$$

where p_{ref} = 1 μPa for underwater noise. The sound pressure level for a given frequency band may be computed directly applying equation (4) on the signal filtered on that band, or it can be computed from the power spectral density $\phi(f,\Delta f)$ as follows:

$$SPL(f,\Delta f) = 10\log_{10}\left(\frac{\phi_{pp}(f,\Delta f)}{p_{ref}^2}\right) \tag{5}$$

In order to identify the contribution of the cavitating propeller, a background noise correction is applied. The background noise has been measured by all the facilities involved, replacing the propeller with a dummy hub and running the facility at the same operational conditions used during propeller tests (same advance speed, shaft rate, depressurization level). Net noise levels are computed based on the signal-to-noise ratio (SNR), which is the difference between the total sound pressure levels (SPL_{s+n}) and the background sound pressure levels (SPL_n):

1. SNR ≥ 10 dB: No correction

$$SPL_s = SPL_{s+n} \tag{6}$$

2. 3 dB ≤ SNR < 10 dB:

$$SPL_S = 10\log_{10}\left(10^{(SPL_{s+n}/10)} - 10^{(SPL_n/10)}\right) \tag{7}$$

3. SNR< 3 dB: results disregarded.

Obtained net noise level SPL_s must be scaled to the reference distance of 1 m. To do this, it is necessary to make some assumptions on the noise propagation process.

The simplest assumption is that of spherical propagation inside the facility, which leads to the Radiated Noise Levels (RNL) as follows:

$$RNL = SPL_s + 20\log_{10}\left(r/r_{ref}\right) \tag{8}$$

where r is the distance between the hydrophone and the propeller, r_{ref} is a reference distance, usually equal to 1 m.

Table 3: Summary of radiated noise database.

Partecipant	Acquisition parameters		Available data							
	Sampling Frequency [kHz]	Duration [s]	SPL		Background noise		20log(r) or TF		Source Strength Level (SL) or Radiated Noise Level (RNL)	
			OTO	Narrowband	OTO	Narrowband	OTO	Narrowband	OTO	Narrowband
MARIN	320	2.4, 1.9	yes	yes	yes	Yes	20log(r)+LM	20log(r)+LM	SL	SL
UNIGE	200	10.5	yes	yes	yes	Yes	TF	TF	SL	SL
SSPA	96	300	yes	yes	yes	Yes	TF	TF	SL	SL
UNEW	50		yes	N.A.	yes	N.A.	20log(r)	N.A.	RNL	N.A.
KRISO	256	60	yes	yes	yes	Yes	20log(r)**	20log(r)**	RNL**	RNL**
NMRI	200	60	yes	yes	Yes*	Yes[1]	20log(r)	20log(r)	RNL	RNL
CNR-INM	to be done	to be done	to be done	to be done	to be done	to be done	to be done	to be done	to be done	to be done

When noise measurements are carried out in model-scale facilities, the noise field is usually different than that in the case of free-field conditions. In order to assess the effects of the confined environment on noise propagation and define a proper correction, a transfer function (TF) needs to be measured by using a known sound source (Tani et al. 2016). The transfer function is then used to derive the Source Strength Levels (SL):

$$SL = SPL_s - TF \quad (6)$$

A slightly different approach is used for measurements carried out in the depressurized wave basin at MARIN. In this case, measurements are carried out at a distance from the source lower than the reverberation radius, which has been previously determined as described in (Lafeber et al. 2015). Thanks to this, reflections from the basin walls and bottom can be neglected and only reflections from the free surface, (i.e. the Lloyd's mirror (LM) effect) must be taken into account with proper formulas. In the present work, a model based on (Ainslie 2010) has been adopted.

Available results, including the application of transfer functions or other scaling formulas, are summarized in Table 3.

3.1 Extrapolation to full scale.

In order to compare all the results of the round robin campaign, scaling to a common condition has been considered. This condition corresponds to the Princess Royal operating at maximum speed in terms of propeller diameter, shaft rotation rate and cavitation number:

- $D_s = 0.75$ [m].
- $n_s = 19.025$ [RPS]
- $\sigma_{ns} = 1.06$

where σ_n is the cavitation number based on the rotation rate, defined as:

$$\sigma_n = \sigma_V J^2 \quad (9)$$

Different formulations are available from literature for extrapolating to full-scale noise spectra. In this work, the ITTC formulation (ITTC 2017) was used:

$$\frac{f_s}{f_m} = \left(\frac{n_s}{n_m}\right)\sqrt{\frac{\sigma_s}{\sigma_m}} \quad (10)$$

$$SPL_s = SPL_m + 20\log_{10}\left[\left(\frac{\sigma_s}{\sigma_m}\right)^w\left(\frac{r_m}{r_s}\right)^x\left(\frac{n_s D_s}{n_m D_m}\right)^y\left(\frac{D_s}{D_m}\right)^z\right] \quad (11)$$

where s stands for ship and m for model. Two sets of exponents are available, resulting in two formulations. One formulation is defined assuming constant acoustic efficiency and is referred to as the "high-frequency" formulation. The second formulation assumes the acoustic efficiency to vary linearly with the Mach number and may be derived also from the Rayleigh-Plesset equation, consequently this second formulation is defined as the "low-frequency" formulation.

In order to focus on a first comparison between the large amount of data resulting from the round robin campaign, only one set of exponents, namely the low-frequency formulation, has been applied. The expected differences in case the high frequency formulation is used are not significant for the aims of the Round Robin campaign. An example of comparison between the two formulations, for a different propeller, is reported in (Lloyd et al. 2018). The exponents used in present work are reported in Table 4 for both constant and proportional bandwidth spectra.

Table 4: Exponents for the low frequency formulation.

Bandwidth	w	X	y	z
Constant	0.75	1	1.5	1.5
Proportional	1	1	2	1

- *Background noise correction yet to be applied.
- **Transfer functions to be reprocessed.

4 RESULTS OVERVIEW

The results of the whole round robin campaign include cavitation observations and noise data for six propeller loading conditions, two shaft inclination and currently six institutions, hence the amount of data is substantial.

In this work, some examples are shown and first general comments on the results are drawn. Deeper analyses will be carried out in future research considering all the data available from different institutions and trying to explain results and to correlate them with the characteristics of the facility, the setup and the procedures employed.

4.1 Cavitation extensions

First, propeller cavitation extensions observed by the different facilities are analysed and compared.
As a general comment, all the extensions observed within the round robin campaign exhibit common features:

- Only tip vortex cavitation and suction side sheet cavitation have been observed for all the loading conditions.
- The tip vortex occurs as a leading edge vortex.
- The largest cavitation, consisting of large sheet cavitation, was always observed for conditions C3 and C9 (i.e. lowest advance ratio and lowest cavitation number).
- The smallest cavitation extent, consisting of a weak tip vortex, was observed for conditions C4 and C10 (i.e. the highest advance ratio and highest cavitation number).
- Cavitation phenomena are only slightly influenced by the effect of the inclined flow, for the shaft inclination angle considered.

In order to analyse the cavitation patterns more in detail, three examples are reported in Figure 2, Figure 3 and Figure 4, focusing on conditions with no shaft inclination.

Starting from the first condition (C3), which is the one with the largest cavitation extent, a fair agreement between the different institutions can be observed in terms of cavitation typology and dynamics, see Figure 2. In all cases, a large sheet cavity is present at blade outer radii, extending over the entire chord and generating cloud cavitation at the trailing edge. The tip vortex is characterized by a rather unstable behaviour and a foamy character, without the presence of a well-defined vortex core.

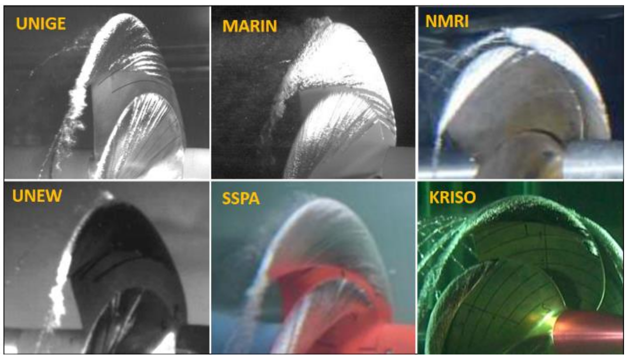

Figure 2: Comparison of cavitation extension for condition C3 ($J = 0.4$, $\sigma_V = 4.5$, $\beta = 0°$).

Trying to compare these results in more detail, some differences may be observed, in particular regarding the extension of the sheet cavity towards lower radii:

- The largest cavity is observed at SSPA.
- Slightly smaller cavitation is present at MARIN, with some streaks at inner radii.
- Similar sheet cavitation is observed at UNEW, but without streaks and slightly less extended.
- The sheet cavitation is further reduced at UNIGE, where some streaks at inner radii are again present.
- The smallest sheet cavitation are observed at KRISO and NMRI.

Smaller differences are observed for the extension of tip vortex cavitation, which is indeed rather similar at all institutions. Only the vortices at NMRI and KRISO show a slightly larger cavitating core.

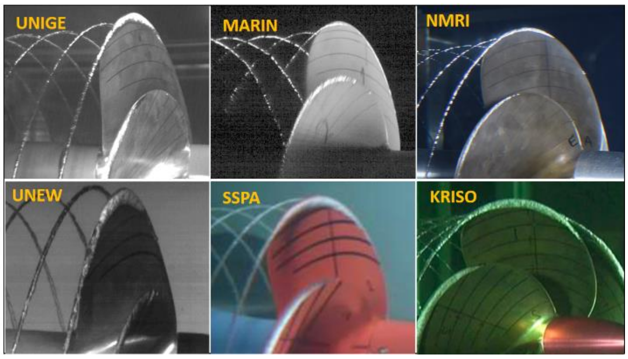

Figure 3: Comparison of cavitation extension for condition C1 ($J = 0.4$, $\sigma_V = 13.9$, $\beta = 0°$).

The loading condition C1 shown in Figure 3 is instead characterized by the presence of a well-defined cavitating tip vortex and a sheet cavitation definitely smaller than for condition C3. In this case, differences between institutions are smaller:

- The largest sheet cavities are probably those observed at SSPA and KRISO.
- Sheet cavities observed in other facilities are similar and it is difficult to rank their extensions (also because of differences in the observation angle and extent).
- The sheet cavitation at MARIN seems slightly more extended in the radial direction with respect to those observed at UNIGE and UNEW, which however seem a bit thicker and more extended in the chordwise direction.

- The sheet cavitation observed at NMRI appears to be intermediate between MARIN, UNIGE and UNEW in terms of both radial and chordwise direction.
- Tip vortices are rather similar each other.

Finally, the loading condition C4 shown in Figure 4 is characterized by the presence of a weak tip vortex for all institutions. This vortex is attached to the blade leading edge or appears in the blades slipstream.

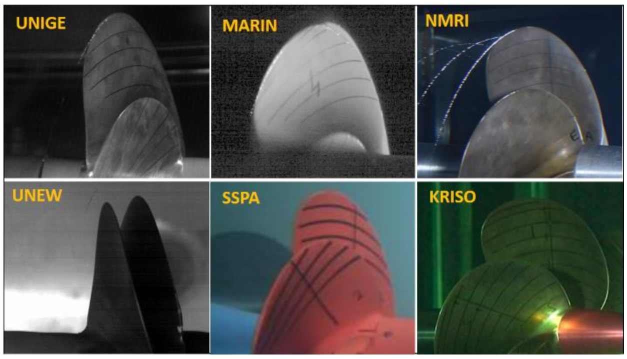

Figure 4: Comparison of cavitation extension for condition C4 ($J = 0.5$, $\sigma_V = 13.9$, $\beta = 0°$).

The agreement between different institutions for this condition is again rather good. The vortex observed at NMRI is slightly larger and more stable than at the other institutes.

The vortex is, however, not visible in the photograph from KRISO. This is due to the intermittent nature of cavitation at inception, for which in some cases it is difficult to capture the cavitation in the photographs, even if cavitation is actually present.

In summary, this qualitative analysis confirms a good overall agreement in terms of the cavitation extents observed by the different institutions. The same cavitation typologies have been observed with similar trends and similar dynamics. Some minor differences, however, are present in terms of dimensions of the cavities, mainly regarding the extent of sheet cavitation at inner propeller radii. These small variations may be mainly ascribed to the different development of the boundary layer on the propeller blades, which may affect cavitation inception on a model propeller, especially at inner radii (Kuiper 1991). This effect could be caused by the differences in Reynolds number in the cavitation experiments and blade treatment employed.

4.2 Underwater Radiated Noise measurements

In analogy with the previous paragraph, an overview of results in terms of noise spectra is given, describing the main results and focusing on some relevant examples.

The analysis is carried out starting from the trends observed by the participants with respect to the different loading conditions and the effect of the inclined flow. Then noise spectra measured by the different institutions are directly compared.

Only full-scale spectra are considered here. That means spectra obtained after having applied the whole processing described in section 3, including also the scaling by means of Equation 10 and Equation 11.

Regarding shaft inclination, some effects have been observed, as for the cavitation patterns, however these effects are rather limited in most cases. The main characteristics of the spectra do not vary and differences in levels are mostly below 10dB, with higher noise levels for the inclined shaft condition. This is the most common trend observed, however some exceptions to the described behaviour exist, needing for ad hoc analyses. As an example, higher noise levels have been measured in some cases without shaft inclination.

From the point of view of the round robin tests and the comparison between all the results, the effects of the shaft inclination on noise spectra are in most cases negligible and consequently, results of tests without shaft inclination only are considered in the present paper. Deeper analyses of tests with inclined inflow will be performed as part of future work.

The noise spectra measured by all the participants in correspondence to different propeller loading conditions, from C1 to C6, are shown in Figure 5. This allows for a first comparison of results, focusing on the global behaviour of cavitation noise rather than a direct comparison between noise levels measured by the participants.

Some common trends may be observed, even if there is a significant variability of results between the participants.

In most cases noise levels increase with cavitation extension, that is, from condition C1 to condition C3 and from condition C4, to condition C6.

Considering conditions characterized by the lower advance ratio (i.e. C1, C2 and C3) a sudden increase of noise levels is observed for some institutions, namely UNIGE, SSPA and NMRI, passing from condition C2 to C3, which is the noisiest condition in this case. Considering spectra measured at MARIN and KRISO this effect is less evident. In particular, at MARIN noise levels increase with the same order described but the sudden large increase for condition C3 is not observed. In addition, condition C3 is not clearly the noisiest condition, featuring noise levels similar to those measured for condition C6. The results obtained at KRISO show noise levels at high frequencies, which are rather similar between all loading conditions, with slightly higher levels for condition C3 on most frequency bands. At low frequency instead, higher levels are observed for condition C2. It should be noted that measurements at KRISO are characterized by very high

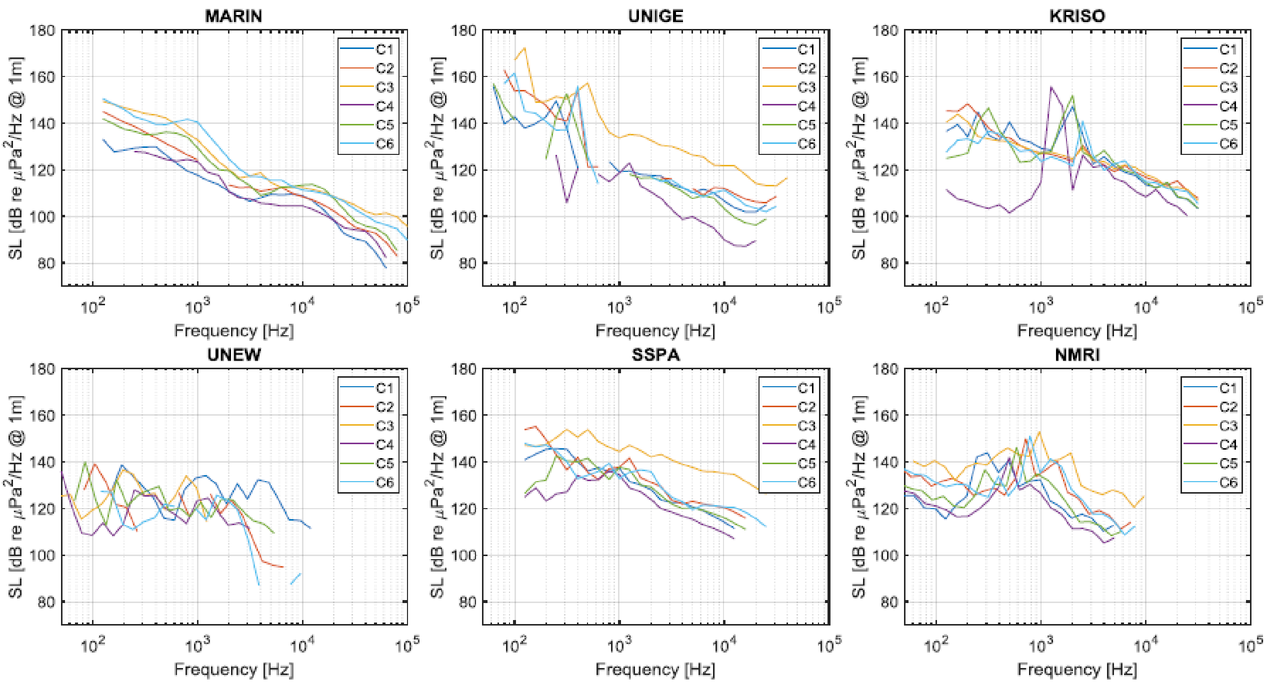

Figure 5: Comparison of noise measured by all the participants in correspondence to different propeller loading conditions.

peaks between 1 kHz and 3 kHz, which are caused by propeller singing. This phenomenon has been observed also by other institutions, see as an example (Tani et al. 2017, Sakamoto et al. 2017), however for measurements at KRISO the intensity of this phenomenon seems larger and its presence must be carefully taken into account when comparing these measurements with other tests.

Finally, considering results from UNEW tests, higher levels at high frequencies are observed for condition C1 while at lower frequencies, peak levels measured for each condition are rather similar, even if centred at different frequencies. It is worth mentioning that spectra measured at UNEW present a characteristic shape, rather different to those of other measurements, probably due to the special hydrophone setup adopted at the time of tests (Aktas et al. 2016b).

Similar comments may be made by analysing the loading conditions with the higher advance ratio (i.e. C4, C5 and C6). In most cases, condition C4, which has the least cavitation, exhibits the lowest noise levels. Spectral levels then increase for conditions C5 and C6.

For some institutions, as UNIGE, KRISO, UNEW and SSPA, levels measured for conditions C5 and C6 are rather similar; slightly higher levels on average have been measured for condition C6, but the difference with respect to condition C5 is lower than that present between conditions C5 and C4. For other institutions, such as MARIN and NMRI, larger increase is evident in noise levels moving from C5 to C6, compared to the difference between C4 and C5.

Looking now at the overall comparison of noise data from the round robin campaign, results for the straight shaft condition are summarized in Figure 6.

The spread of noise data seems significant: for some frequency bands, differences are even larger than 20 dB. However, this large spread is also caused by the presence of tonal noise components such as propeller singing, mechanical vibrations, drive train noise etc. Actually, these noise components are often not eliminated by the background noise correction because in some cases (e.g. drive train noise) they may be more intense when the propeller is present (compared to the situation with a dummy hub, which does not put a loading on the drive train). Other noise components, such as propeller singing, are not eliminated because they are effectively part of propeller noise, but they do not scale similarly on other propeller models. These tones could be effectively identified by analysing narrowband noise spectra and possibly be filtered away using suitable processing technique, as the adoption of a smoothing filter (Lafeber and Lloyd 2017).

Focusing on the broadband noise components and neglecting the anomalous peaks in the spectra, the agreement between results is significantly increased, even if the variation of noise levels is still remarkable. Actually, neglecting the frequency bands for which tonal noise is

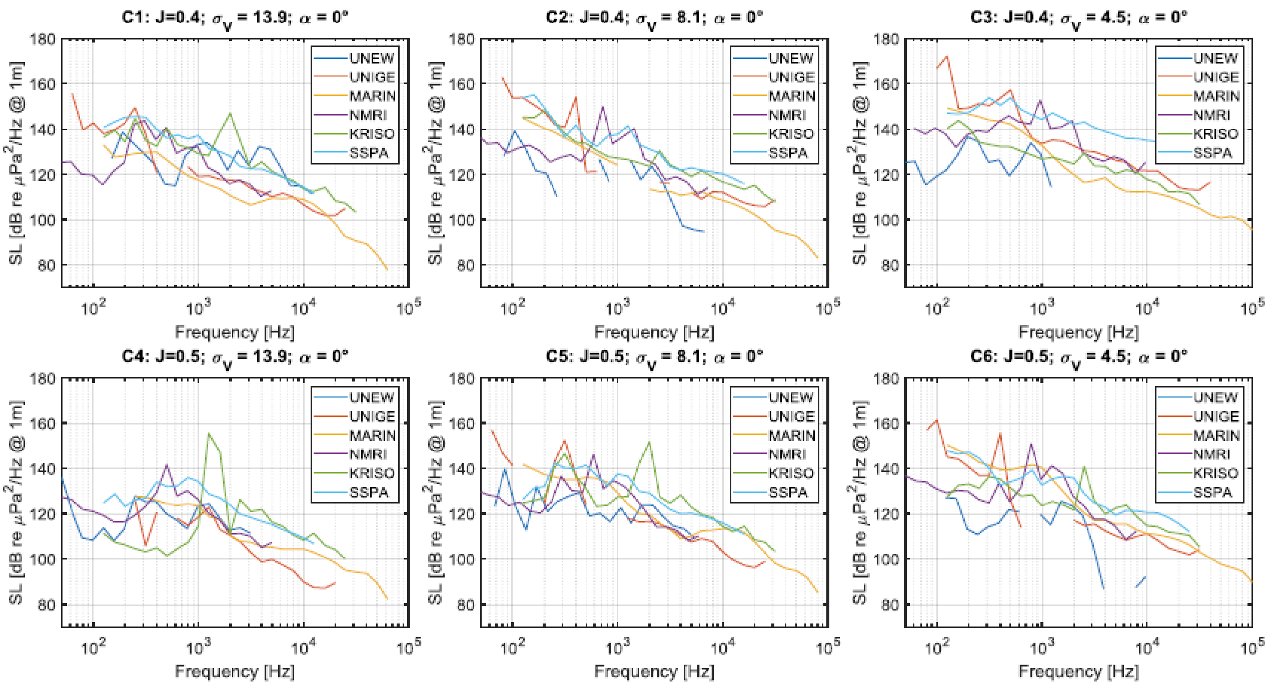

Figure 6: comparison of measured radiated noise within all the participants, conditions without shaft inclination.

dominant, a band of variation of about 10 dB of predicted noise levels is observed on average.

At medium-high frequency (above 2 kHz), higher noise levels have been measured at SSPA and KRISO, while the lowest levels are in most cases those measured at UNIGE and MARIN. For conditions C2 and C6 very low noise has been measured at UNEW, but this could be partially due also to noise absorption in the facility caused by free bubbles.

Considering instead the low frequency region (below 2 kHz), higher noise levels have been measured at SSPA, UNIGE and, for some conditions NMRI and KRISO.

In summary, there are several similarities within most of the results obtained by the participants, especially in terms of main characteristics of the noise spectra, however, anomalies are also present and the spread of measured noise levels is generally significant.

The differences between noise levels are only partially in agreement with cavitation extensions observed. Actually, the largest sheet cavitation for most conditions was probably that observed at SSPA, where also the higher noise levels have been measured, especially at high frequency. Analogously, smaller sheet cavitation at inner propeller radii, especially for condition C3, has been observed at UNIGE, where noise measured at high frequency is within the lower measured. On the other hand, considering measurements carried out at MARIN, the extension of sheet cavitation was similar to that at SSPA, while high-frequency noise levels are comparable to those measured at UNIGE.

The previous particular cases have been described to exemplify a general trend: observed discrepancies in noise levels are not always consistent with differences within cavitation patterns. In order to clarify how much the spread of noise data may correlate to observed cavitation patterns and the sensitivity of measured radiated noise to small variations of the cavitation extensions should be further investigated. Anyway, this aspect seems insufficient to explain the large variation of measured noise levels.

The cavitation dynamics should be considered, in addition to the size of cavities, introducing further differences within the cavitation experiments carried out by the participants, yet from the analysis of available data large differences in cavitation dynamics are not evident as well.

As an empirical remark, it is also worth noticing that in many cases, the lowest noise levels at high frequency have been measured at MARIN and UNIGE that are also the facilities were the lowest Reynolds number values have been used, especially for J = 0.4.

In order to understand the differences between the available noise data, further aspects should be carefully taken into account, such as the effects of particular hydrophone configuration, or the facility reverberation.

It is also important to note that transfer function corrections have currently only been applied by some of the participants and this may introduce further uncertainties. This issue may be crucial especially for those cases for which reverberation and general propagation effects may be more important, as for smaller facilities or particular hydrophone configurations.

5 CONCLUSIONS

A round robin test campaign has been carried out within the Noise Community of Practice of the HydroTesting Forum on propeller noise measurements in model scale.

An overall comparison of results is carried out and, where discrepancies are observed, an attempt has been made to find reasonable explanations for such discrepancies.

This comparative analysis of available data demonstrates that a good agreement has been obtained in terms of cavitation extent. The same cavitation phenomena, with similar extent and dynamic behaviour, have been observed by all the participants. Looking into details, some differences are present, which may be caused by a number of factors. In particular, those aspects having larger influence on the development of the boundary layer on propeller blades are probably the most relevant.

Moving to the comparison of noise data, the interpretation of results is definitely more complex. Common trends and similar spectral characteristics have been observed. However, the spread of noise levels is significant. This is not surprising, when dealing with such a complex topic as cavitating propeller noise, nevertheless such bands of variation are remarkable and a first effort to explain these results has been carried out.

Observed differences in cavitation patterns may of course play a role also on noise, however they are in most cases not sufficient to explain the differences within noise levels measured at different facilities. Other possible explanations are those related to the noise propagation process, such as reverberation, multiple reflections and the effects of the hydrophone configuration. These aspects may be partially taken into account by applying transfer functions corrections. However, those have not been applied by all of the participants.

The discussions reported in the present work and possible explanations of results are far from being exhaustive.

Further studies are needed in order to investigate and quantify the effects of mentioned aspects and all other possible phenomena influencing measurement results. From this point of view, measured data, with all additional investigations carried out by the participants, constitute a valuable source of information to further increase the understanding of cavitating propellers radiated noise and its model scale measurement.

Furthermore, the round robin campaign is not finished; tests at CNR-INM are yet to be carried out. These further tests will provide an important opportunity to carry out additional investigations based on the results currently available. This would allow analysis and possibly clarification of some of the critical aspects identified by the present work, by running ad hoc experiments.

In addition, this invaluable dataset has also been built with the important aim of making it accessible on request to everyone interested in studying propeller noise, posing the basis to become an important benchmark for propeller cavitation noise.

REFERENCES

AA.VV, "IMO MEPC.1/Circ.833: Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life", 2014.

AA.VV. "Report on CISMaRT/Transport Canada Workshop on Ship Noise Mitigation Technologies for a Quieter Ocean", January 2019.

Ainslie, M., Principles of sonar performance modelling. Springer Praxis, Berlin/Heidelberg, 2010. doi: 10.1007/978-3-540-87662-5.

Aktas, B., Atlar, M., Turkmen, S., Shi, W., Sampson, R., Korkut, E., Fitzsimmons, P., 2016a. Propeller cavitation noise investigations of a research vessel using medium size cavitation tunnel tests and full-scale trials. Ocean Eng. 120, 122–135. https://doi.org/10.1016/j.oceaneng.2015.12.040.

Aktas, B., Atlar, M., Turkmen, S., Korkut, E., Fitzsimmons, P., 2016b. Systematic cavitation tunnel tests of a Propeller in uniform and inclined flow conditions as part of a round robin test campaign. Ocean Eng. 120, 136–151. https://doi.org/10.1016/j. oceaneng.2015.12.015.

Bark, G., "Prediction of propeller cavitation noise from model tests and its comparison with full scale data", Journal of Fluids Engineering, Vol. 107, pp 112-119, 1985.

Billet, M., Atlar, M., Briancon-Marjollet, L., Ceccio, S.L., Kim, Y.G., Oshima, A., Semionicheva, E., Song, I.H., 2002. The Specialist Committee on Water Quality and Cavitation Final Report and Recommendations to the 23rd ITTC. 23rd ITTC II, pp. 429–491.

Blake, W.K., Sevik, M.M., "Recent developments in cavitation noise research" Int. Symp. On Cavitation Noise, ASME, 1982.

Briancon, L., Fournier, P., Fréchou, D., 2013, "Marine Propeller Noise Measurements Techniques in Hydroacoustics Tunnel", Symposium on Advanced Measurement Techniques, AMT'13, Gdansk, Poland.

Dambra, R, and Firenze, E (2015). "Underwater Radiat-ed Noise of a Small Vessel", The 22nd International Congress on Sound and Vibration, Florence Italy.

Hildebrand, J.A., "Anthropogenic and natural sources of ambient noise in the ocean", Marine ecology Progress Series, Vol. 395, 2009.

ITTC, "Report of the Specialist Committee on Hydrodynamic Noise", 27th ITTC Conference, Copenhagen, 2014.

ITTC Specialist Committee on Hydrodynamic Noise, 2017. Model-scale propeller cavitation noise measurements. In: Recommended Procedures and Guidelines 7.5-02-01-05 International Towing Tank Conference.

Kamiirisa, Hikaru. (2001). The Effect of Water Quality Characteristics on Cavitation Noise.

Korkut, E. 1999 An investigation into the scale effects on cavitation inception and noise inmarine propellers. PhD thesis, University of Newcastle upon Tyne, UK.

Kuiper, G. 1981 Cavitation inception on ship propeller models. PhD thesis, University of Delft, The Netherlands.

Lafeber, F.H., Bosschers, J., de Jong, C., Graafland, F., 2015, "Acoustic reverberation measurements in the depressurized towing tank", 4th International Conference on Advanced Model Measurement Technologies for the Maritime Industry AMT'15, Istanbul, Turkey.

Lafeber, F.H., Bosschers, J., 2016. Validation of computational and experimental prediction methods for the underwater radiated noise of a small research vessel. In: Proceedings of PRADS 2016, Copenhagen, Denmark.

Lafeber, F. H., Lloyd, T., "Round robin test on the underwater radiated noise of a cavitating ship propeller in open water", 5th International Conference on Advanced Model Measurement Technologies for the Maritime Industry AMT'17, Glasgow, UK.

Lloyd, T., Lafeber, F.H., Bosschers, J., 2018, "Investigation and Validation of Procedures for Cavitation Noise Prediction from Model-Scale Measurements", 32nd Symposium on Naval Hydrodynamics, 5-10 August, Hamburg, Germany.

Løvik, A., "Scaling of propeller cavitation noise", Noise sources in ships, Nordforsk, Stockholm, Sweden, 1981.

Sakamoto, N., Fujisawa, J., Sawada, Y., Ukon, Y, Kamiirisa, H, "Measurement of cavitation noise radiated from a marine propeller with and without shaft inclination", , 5th International Conference on Advanced Model Measurement Technologies for the Maritime Industry AMT'17, Glasgow, UK.

Tani, G., Viviani, M., Gaggero, T., Hallander, J., Johansson, T., "Evaluation of methods to measure acoustic transfer functions in cavitation tunnels", 4th Advanced Model Measurement Technology for the EU Maritime Industry AMT'15, Istanbul, Turkey, 2015.

Tani, G., Viviani, M., Armelloni, E., Nataletti, M., 2016. Cavitation tunnel acoustic characterisation and application to model propeller radiated noise measurements at different functioning conditions. Proc. IME M J. Eng. Marit. Environ. 230, 250–266.

Tani, G., Aktas, B., Viviani, M., Atlar, M., 2017. Two medium size cavitation tunnel hydro-acoustic benchmark experiment comparisons as part of a round robin test campaign. Ocean Eng. 138, 179–207. https://doi.org/10.1016/j.oceaneng.2017.04. 010.

Tani, G., Aktas, B., Viviani, M., Yilmaz, N., Miglianti, F., Ferrando, M., Atlar, M., "Cavitation tunnel tests for "The Princess Royal" model propeller behind a 2-dimensional wake screen", Ocean Engineering, Volume 172, 2019, Pages 829-843, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2018.11.017.

Turkmen, S., Aktas, B., Atlar, M., Sasaki, N., Sampson, R., Shi, W., 2017. On-board measurement techniques to quantify underwater radiated noise level. Ocean Eng. 130, 166–175. https://doi.org/10.1016/j.oceaneng.2016.11.070.