The Specialist Committee on Hydrodynamic Noise

Final Report and Recommendations to the 28th ITTC

1 OVERVIEW

This report summarizes the work of the Specialist Committee on Hydrodynamic Noise for the 28th ITTC.

1.1 Membership and Meetings

The 27th ITTC appointed the following members to serve on the Specialist Committee on Hydrodynamic Noise:

- Johan Bosschers (chair)
  MARIN, Netherlands
- Gil Hwan Choi
  Hyundai HI, Korea
- Theodore Farabee (secretary)
  NSWCCD, USA
- Didier Fréchou
  DGA/H, France
- Emin Korkut
  Istanbul Technical University, Turkey
- Kei Sato
  Mitsubishi Heavy Ind., Japan
- Tuomas Sipilä
  VTT, Finland
- Denghai Tang
  CSSRC, China
- Claudio Testa
  CNR-INSEAN, Italy

The committee held four meetings at the following locations:

- Istanbul, Turkey at ITU on March 12-13, 2015
- Espoo, Finland at VTT on February 24-25, 2016
- Washington, USA at NSWC/CD on October 12-13, 2016
- Val-de-Reuil, France, at DGA/H on April 27-28, 2017

1.2 Recommendations of the 27th ITTC

The 27th ITTC recommended the Specialist Committee on Hydrodynamic Noise for the 28th ITTC to address the following activities:

(1) Continue development of the guidelines produced during the 27th ITTC and monitor how these guidelines are being implemented by the towing tank community.

(2) Identify scale effects in prediction of hydrodynamically generated noises (flow noise, cavitation noise, etc.).

(3) Examine the possibilities to predict full scale values (at ‘various’ operational conditions) from model scale noise measurements.

(4) Review uncertainties associated with model scale noise measurements and full scale noise measurements, including variability between sister ships and influence of operational conditions during sea trials, such as manoeuvring and sea state.

(5) Check the existing methodologies regarding full scale noise measurements in shallow and restricted water and provide, if possible, guidelines. Establish communication with ISO working groups active on this topic.

(6) Update the overview of national and international regulations and standards regarding hydrodynamic noise.

(7) Review the developments of predicting methods (theoretical and numerical) for underwater noise sources characterisation and for far field propagation.

(8) Define and, if possible, conduct benchmarking tests of model test noise measurements, preferably for a ship for which full scale noise measurements are available.

2 INTRODUCTION

Sound is defined as mechanical disturbance, which is propagated in an elastic medium, of such character as to be capable of exciting the sensation of hearing (BSRA, 1982). It is generated whenever there is a relative motion between two fluids or between the fluids and a surface. Noise is described as unwanted sound which interferes with the normal functioning of a system. The noise generated by a ship can be grouped into two main categories (Carlton, 2012) self noise and radiated noise. The underwater radiated noise of ships can be important for various reasons. For naval vessels the underwater radiated noise is part of the ship signature in relation to threats such as submarines, mines and torpedoes. Noise can also be relevant in terms of the operation of underwater acoustic equipment such as sonar. The noise level of the ship adds to the background noise of the equipment and therefore should be below a certain level such that the sonar can achieve a specified operating range. One then speaks of self-noise instead of radiated noise. High underwater noise levels may also influence fish behaviour, which has resulted in noise requirements for fishery research vessels. Nowadays, there also is an increasing concern regarding the adverse influence of underwater noise, including shipping noise, on marine wildlife. This has resulted in a wide variety of scientific, political and technical activities on shipping noise as reviewed by the 27th ITTC Specialist Committee on Hydrodynamic Noise

Underwater noise emission of vessels can be grouped according to Urick (1983) and Ross (1976) into three major classes:

- Machinery noise caused by the main propulsion system and auxiliary equipment.
- Propeller noise caused by flow phenomena on the propeller as it operates in the wake field of the ship hull.
- Hydrodynamic (flow) noise caused by flow of water along the ship hull.

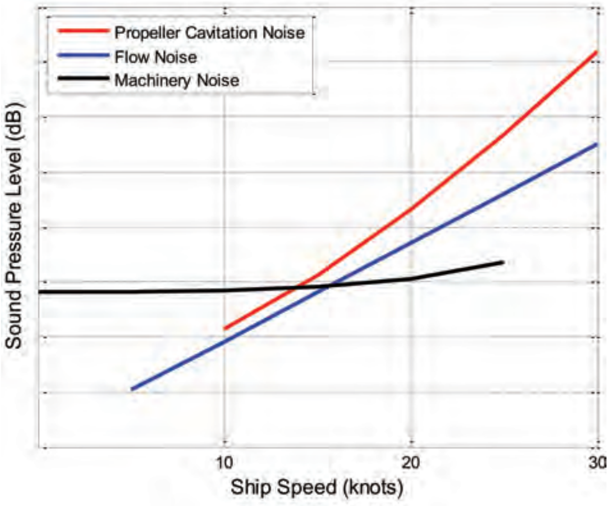


Figure 1 Illustration of variation of ship underwater radiated noise contributors with ship speed

Machinery noise is structure-borne noise as the noise is generated by the ship structure excited by the machinery equipment. The other two classes generate fluid-borne noise. The noise exciting mechanisms in each class may be of different kind. Examples of noise that are of a mechanical origin include rotating unbalance, gear teeth loading, combustion processes and bearing friction. Veikonheimo et al. (2016) showed that the underwater noise emissions from the electric motor located inside the submerged pod housing of an azimuthing propulsion device can be equally important to the hydrodynamic noise from the propellers. Fluid flow phenomena like cavitation, turbulence, vortex shedding, displacement and lift are a source of both near field pressure fluctuations and radiated noise. Propeller noise is composed of non-cavitating propeller noise and cavitation noise. Once cavitation occurs, it is typically the most dominant noise source, as illustrated in Figure 1. Cavitation normally occurs first on the propeller and only at high ship speed it also occurs on struts, rudders, and stabilizers. Therefore, most of the activities related to hydrodynamic shipping noise focus on propeller cavitation noise as does this report.

With respect to discussions of noise emission from ships, use of the term 'hydrodynamic noise' is too restrictive and, more importantly, misleading and will be replaced in the following by the term 'underwater radiated noise' (URN) or in short 'noise'.

3 NOISE REGULATION

A review of activities related to regulation of underwater noise of shipping is provided by the 27th ITTC Specialist Committee on Hydrodynamic Noise. Below an update is given on these activities.

EU: The EU Marine Strategy Framework Directive (2008/56/EC) specifically mentions the problem of noise pollution and provides a legal framework for addressing this issue. The Directive identifies 11 environmental descriptors to achieve a Good Environmental Status (GES) in European Seas by 2020, and descriptor 11.2 states: "Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate". Member States should develop monitoring programmes to enable the state of marine waters concerned. The background of this indicator is that masking of biologically important signals may occur due to elevated ambient noise from human activities such as shipping. In the long term this could also induce stress in the receivers. The directive is discussed in detail by Tasker (2010), Piha (2012) and Van der Graaf et al. (2012).

Initial monitoring guidelines were developed, Dekeling et al. (2014), and these were further discussed in a workshop, Ferreira (2016). Considerable experience was built up in the EU sponsored BIAS project (www.bias-project.eu) in which noise was monitored at 39 locations throughout 2014 in the Baltic Sea, Nikopoloulos et al. (2016). A conclusion from this project was that the largest noise levels are measured near shipping lanes but that there are large seasonal and likely annual variations in ambient noise levels. Identifying statistically significant trends (if they exist) in ambient noise levels remains challenging and probably will take many years. Between 2012 and 2015, two multinational collaborative projects were partly funded by the 7th Framework Programme of the European Commission with the goal to develop tools to investigate and mitigate the effects of underwater noise generated by shipping. These projects are SONIC (www.sonic-project.eu) and AQUO (www.aquo.eu). Both projects included a combination of computational modelling, model scale measurement and full scale measurement of propeller cavitation noise. The results of the AQUO and SONIC project are summarized in a joint guidelines report for regulation on underwater noise from commercial shipping (Baudin and Mumm, 2015). In the AQUO, BIAS, and SONIC projects noise mapping of shipping noise was applied. Noise propagation models were applied in specific parts of EU waters where the ship noise levels were estimated from AIS data combined with a model for the ship (noise) source strength. The models used for the ship source strength are simple empirical models with main parameters being ship speed and ship length.

The noise monitoring task groups include the ACCOBAMS, ASCOBAMS and OSPAR organizations. Various countries in the EU are setting up long term noise monitoring stations to comply with the EU directive.

United States: There have been no significant changes to underwater noise regulations in the United States (US) from that reported in the prior Committee Report. The primary regulatory policies are the National Environmental Policy Act (NEPA, 1969), the Marine Mammal Protection Act (MMPA, 1972), the Endangered Species Act (ESA, 1973), and the Magnuson-Stevens Fishery Conservation and Management Act (MSA, 1976). Generally, enforcement of these policies is handled by either the Department of Interior's US Fish and Wildlife Service (FWS) or the National Marine Fishers Service (NMFS) of the National Oceanic and Atmospheric Administration in the Department of Interior.

Regarding new activities since the last Committee report, in February 2016 the FWS and NMFS issued a joint policy revision stating a renewed commitment by the Services and State fish and wildlife agencies to work together in conserving imperiled wildlife, the intent being to avail the federal Services of the extensive knowledge of local issues developed by the State agencies. And, in September 2016, NOAA published the Ocean Noise Strategy Roadmap (2016) which lays the framework "to support the agency's use of its capabilities and authorities to more effectively understand and address the effects of noise on protected species and acoustic habitats."

Asia: As far as known to the committee, there are no activities related to regulation of underwater radiated noise of ships in Asia.

IMO: After the release of its non-mandatory 'Guidelines for the Reduction of Underwater Noise from Commercial Shipping' in 2014, no new activities within IMO have been reported.

ISO: Various ISO standards related to underwater radiated noise have been developed or are being developed. A review is given in Table 1.

Table 1 Review of ISO standards (including standards in development)

• ISO 17208-1: 2016 Underwater acoustics-Quantities and procedures for description and measurement of underwater sound from ships-Part 1: Requirements for precision measurements in deep water used for comparison purposes
• ISO 18405:2017 Underwater acoustics-Terminology
• ISO/CD 17208-2:2016. Underwater acoustics-Quantities and procedures for description and measurement of underwater sound from ships-Part 2: Determination of source level from deep water measurements (under preparation in ISO/TC43/SC3)
• ISO/NP 17208-3:2016 (Proposal Stage) Underwater acoustics-Quantities and procedures for description and measurement of underwater sound from ships-Part 3: Requirements for measurements in shallow water
• ISO/DIS 20233. Ships and marine technology-Model test method for propeller cavitation noise evaluation in ship design (under preparation in ISO/TC8/SC8/WG14)

Classification Societies: At present three classification societies have developed specific class rules for underwater radiated noise. DNV-GL released its Comfort class rules in 2010 that specifies noise limits for five classes of vessels: i) Acoustic (ships involved in hydro-acoustic measures); ii) Seismic (ships involved in seismic surveys); iii) Fishery; iv) Research; and, v) Environmental (any vessel which require controlled environmental noise emission). BV has released rule NR614 on underwater radiated noise in 2014 (with an update in 2017) which specifies noise limits for a "URN-controlled vessel" and a "URN-advanced vessel". The noise limits for a "URN-specified vessel" are specified on a case-by-case study but may for instance consist of the ICES 209 norm. RINA has released the DOLPHIN class in 2017 in which underwater radiated noise limits are defined for a "Quiet Ship" and for a "Transit Ship" while noise limits are also given for yachts and pleasure yachts.

Other: New activities on underwater

noise regulation have started on a regional level. Two harbour cities in Canada, Port of Prince Rupert and Port of Vancouver, have in 2017 included underwater noise in their program to stimulate green shipping by cruise vessels and cargo vessels. Ships that comply with BV URN notation, DNV SILENT-E class or RINA DOLPHIN class are eligible for Tier 3 (50%) / gold level (47%) discount for the Port of Prince Rupert and Port of Vancouver, respectively. Ships that use noise reduction technologies such as Propeller Boss Cap Fins (PBCF), Schneekluth duct or Becker Mewis duct are eligible for a bronze level (23%) discount for the Port of Vancouver.

There are a number of environmental programs or certificates by which maritime companies, such as ship yards, ship owners, and ports and terminals, can establish, monitor and reduce their environmental footprint. A program that in 2017 will include underwater noise as an indicator is the ‘Green Marine’ program.

4 REVIEW OF SCALE EFFECTS

4.1 Introduction

Sources of ship underwater hydrodynamic noise result from a variety of complex flow-ship interactions. Due to this complexity a range of different scale effects must be considered in predicting hydrodynamically generated noises based on model scale studies. The first step in identifying important scale effects is to consider the types of noise sources that may exist.

As discussed earlier and in the Committee’s Final Report of the 27th ITTC (ITTC, 2014) and illustrated in Figure 2, there are a number of potential sources of ship generated underwater noise, each of which may be important depending on the type of vessel and the degree of noise quieting incorporated in the design. While all of these sources can collectively be termed flow noise sources, noise from the propeller is often separately termed ‘propeller noise’ and when that noise is dominated by propeller cavitation, the noise is termed ‘cavitation noise’.

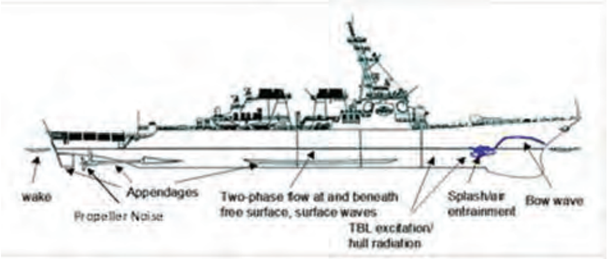


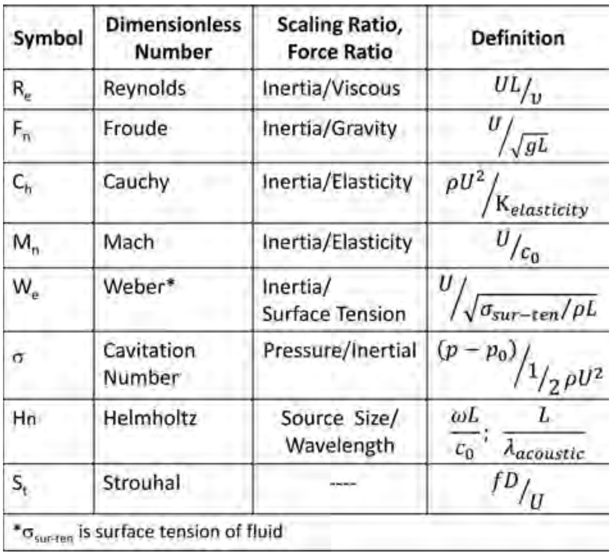
Figure 2 Hydrodynamic related Noise Sources

Scaling of hydrodynamically generated noise requires consideration be given to: i) geometrical, ii) kinematic, and iii) dynamic similarity. Geometrical similarity requires that Model (M) and Ship (S) scale structures have the same shape. This is expressed by all linear dimensions (L) having the same scale ratio, λ: $\lambda = L_S/L_M$. Kinematic similarity requires flow rates of change be similar between model and ship scale (similar streamlines). An example of kinematic similitude is running a (geometrically scaled) model propeller at the same advance ratio as a ship scale propeller thus ensuring the ratio of propeller tip speed to advance speed is the same. Dynamic similitude requires the ratio of forces between model scale and ship scale be constant (geometrical similitude implicitly assumed).

For hydrodynamic noise, consideration needs to be given to similitude scaling of both hydrodynamic and acoustic mechanisms. Standard dimensionless parameters of the variables that are important to hydrodynamic noise are given in Table 2.

The similitude requirements for noise sources need to be considered in establishing a model scale testing campaign. Clearly, for a number of mechanisms not all similitude requirements can be met with a single scale model study. For example, if both viscous and gravity forces are important then full similitude requires matching of both the Reynolds and Froude number. However, since the power dependence between flow velocity and length scale are different for the two, satisfying both similitude requirements is not possible. The consequence of not matching all similitude requires needs to be understood.

Table 2 Dimensionless numbers for hydrodynamic noise similitude



Symbol	Dimensionless Number	Scaling Ratio, Force Ratio	Definition
R_e	Reynolds	Inertia/Viscous	UL/υ
F_n	Froude	Inertia/Gravity	$U/\sqrt{gL}$
C_h	Cauchy	Inertia/Elasticity	$\rho U^2/K_{elasticity}$
M_n	Mach	Inertia/Elasticity	U/c_0
W_e	Weber*	Inertia/ Surface Tension	$U/\sqrt{\sigma_{sur-ten}/\rho L}$
σ	Cavitation Number	Pressure/Inertial	$(p-p_0)/\tfrac{1}{2}\rho U^2$
Hn	Helmholtz	Source Size/ Wavelength	$\frac{\omega L}{c_0}$; $\frac{L}{\lambda_{acoustic}}$
S_t	Strouhal	----	fD/U

*$\sigma_{sur\text{-}ten}$ is surface tension of fluid

4.2 Ship Hull Noise Related

4.2.1 Flow Noise

The topic of noise resulting from flow-structure interactions is extensively addressed in the literature (for example the compendium publications by Blake 1986, and Howe 1998). A cursory review of the flow noise mechanisms illustrated in Figure 2 shows there are many and varied types of possible flow-structure noise sources which complicates discussions of scale effects. Flow noise sources can be grouped into one of two classes based on spectral character; broadband or narrowband. Narrowband sources entail flow shedding excitation of a structural resonance resulting in strong ‘tonal’ character which occurs at specific Strouhal numbers. Broadband sources are ones for which there is no frequency selectivity for either the excitation (flow) or the structural response.

For narrowband sources frequency similitude between model and full scale is generally achieved through Strouhal scaling ($S = fD/U$) assuming model scale testing is done at reasonable Reynolds number. However, the resonance frequency of most scale-model systems do not scale proportional to length and hence, even if a model is a direct scale replicate and testing follows Strouhal similitude, proper coincidence between the vortical flow and structural resonance may not occur. Scale effects for broadband sources must consider scaling of both flow-generated forces (e.g., unsteady surface pressures) and structural-acoustic characteristics of the flow surface. Achieving proper similitude of both is effectively not possible and separate or multiple evaluations are required to address such sources. However, as illustrated in Figure 1, flow noise sources are not currently a primary contributor to ship underwater noise.

4.2.2 Two Phase Flow Noise

The presence of bubbles in the ocean (two phase), whether in-situ or ship generated can be an important issue to hydrodynamic noise. The generation of bubbles can create noise and the presence of bubbles can appreciably alter the acoustic propagation characteristics.

de Jong et al. (2009) used model scale experiments to develop possible scaling laws for noise generated by bow-area wave dynamics. Noise sources were found to correlate with the location of the breaking of the first and second wave crests of the bow wave system. Noise from wave breaking in the stern was also observed but not investigated. It was determined that the generation of air bubbles during these free-surface interactions plays an essential role in the generation of the noise. The important noise scaling parameters were found to include bubble creation rate (air entrainment), the bubble size distribution, and overall void fraction (fraction of air in volume of two-phase fluid).

Due to weather conditions and the hydrodynamic characteristics of a ship, the water in which the ship operates may be characterized as two-phase, a fluid that is predominantly water but also contains air bubbles of various sizes with the bubble size and volume varying with water depth. The presence of bubbles, even in small quantities can potentially have a marked influence on acoustic propagation characteristics.

If bubble density is low, each bubble can behave as a simple spherical oscillator. An approximate relationship for determining the fundamental resonance frequency f (spherical oscillations) of a small air bubble in water at a depth d_b (in meters) is given by Medwin and Clay (1977) as

$$fr_b \cong 3.25 \times \sqrt{1 + {}^{d}b/1\ \mathrm{m}}\,(\mathrm{m/s})$$

where r_b is the bubble radius and the fr_b product has units of m/s. Depending on the distribution of bubbles, a group of bubbles can interact collectively to exhibit characteristics of a bubble cloud or a bubble of the size of the group.

4.3 Propeller Inflow

The contribution of the hull wake on propeller performance, especially for cavitation and inboard/outboard noise, has been reported in many research studies since the 1970's and is routinely taken into account in propeller design. Although all three components of the hull wake flow velocities are important to the performance analysis of a propeller, the axial wake is the most important component dominating the propeller's loading characteristics. Cavitation noise is directly dependent on the blade loading. This requires that cavitation inception, as well as the cavitation extend on the blade for developed cavitation, at model scale correctly represent the full scale cavitation conditions. Because the similarity of Reynolds number cannot be obtained at model test for practical reasons, the model wake field is not representative of the full scale wake field. Different strategies for model testing have been used to get a model scale propeller inflow as close as possible to the full scale propeller inflow. In large cavitation facilities (Vacuum tank or Large Tunnel), the current practice is to test the propellers with the complete hull geometrically scaled. For cavitation tunnels, the maximum achievable flow speed is generally used to achieve the test at the highest Reynolds number. Other methods which have been reported by the 26th ITTC Specialist Committee on Wake Scaling, are based on a reproducing the full scale wake predicted using either CFD or scaled model wake measurements. Methods applied for the wake are:

Dummy hull model with wire grids (Figure 3) or wire grids alone. This empirical method is well dedicated to small and medium size cavitation tunnels.

Modified hull model also called smart dummy as shown in Figure 4.

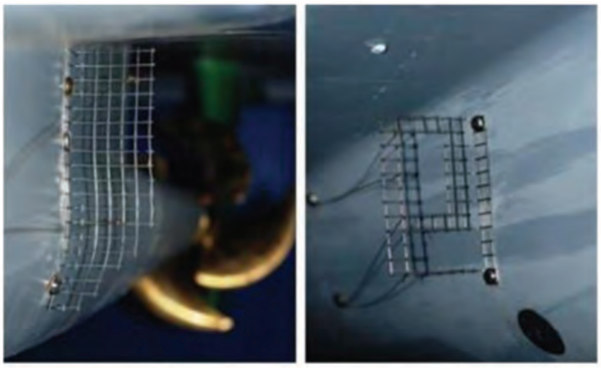


Figure 3 Example of dummy model with wire grids, Photograph from SVA

It should be noted that the wake scaling is not only important for single screw propeller but also for twin screws propellers. In the first case, the propeller is mainly operating in the wake of the ship hull boundary layer. In the second case, the propellers blades are operating in the boundary layer of the hull when reaching the upper position. The use of the smart dummy hull model leads to additional costs because a specific hull model is required for the cavitation and noise model test. More studies are required to generate guidelines for designing a smart dummy hull from a geosim hull.

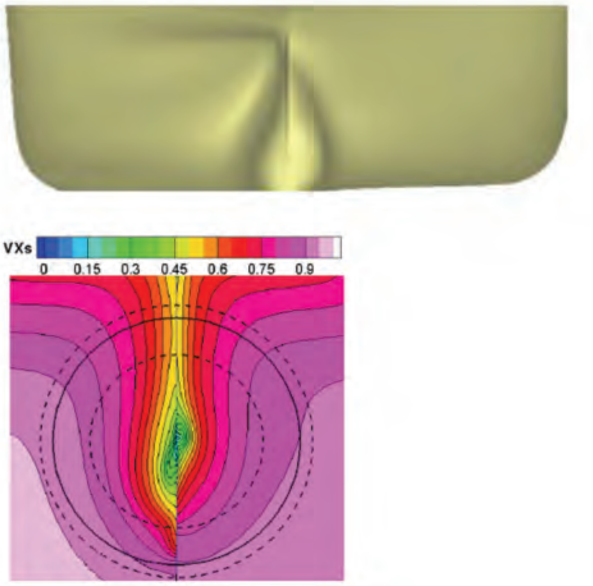


Figure 4 View from behind the Smart Dummy design (left), and the original geosim hull (right) and corresponding axial wake velocity (Schuiling et al. 2011)

4.4 Non-Cavitating Propeller

A (fixed pitch) propeller will operate in a non-cavitating condition at low ship speeds. The noise radiated from a non-cavitating propeller is much less intensive compared to a cavitating propeller. For this condition, ship noise is dominantly due to machinery alone or by machinery and the propulsion system. For some ships, such as fishery research vessels, non-cavitating propeller noise still needs to be evaluated and controlled.

Non-cavitating propeller noise can be categorized as; low frequency tonal noise when the propeller operates in the non-uniform inflow; low frequency broadband noise when propeller operates in the fluctuating turbulent inflow; and, high frequency broadband noise when local boundary layer and vortex flow interact with the blade trailing edge. Compared to cavitation noise, non-cavitating noise measurements require more careful arrangements and installations of the model and measuring system in order to reduce the background noise.

Scale effects on non-cavitating propeller noise are mainly caused by the boundary layer flow of the ship hull, and thus the wake field or propeller inflow, and also caused by the boundary layer and vortex flow of blades and their interactions.

With the development of numerical prediction methods for non-cavitating propeller noise, which is discussed in the subsequent sections of the report, Yang et al. (2013) adopted the coupling method (URANS for flow simulation and FWH for acoustic analogy) to study the scale effects of non-cavitating propeller noise in a given nominal wake of the ship. Three scaled geometrically similar propellers with diameter 250 mm, 500 mm and 1000 mm were simulated and the results were scaled to the same scale by using eq. (1), provided below, where $k = 1$. It suggested that the model scale should be chosen as large as possible considering the test facility or numerical simulation capabilities, and that the scale effect needs to be further investigated to get correction factors which might be related to the Reynolds number for the scaling method. Frechou et al. (2004) use similar flow speed in a model test as at full scale and show good agreement for the non-cavitating propeller noise spectrum.

From similarity analysis, Levkovsky (2002) presented a scaling method for predicting non-cavitating propeller noise, as shown in eq. (1), where subscript S, and M are for ship and model, respectively. $k = k(f, Re, Ch)$ is a coefficient to account for scale effects which is a function of frequency (f), Reynolds number (Re), and Cauchy number (Ch). It should be determined from statistical analyses of numerous test results of model and full scale propellers.

$$f_S = f_M \cdot \frac{n_S}{n_M}$$
$$L_S = L_M \cdot \left(\frac{n_S}{n_M}\right)^5 \cdot \left(\frac{D_S}{D_M}\right)^7 \cdot \left(\frac{r_M}{r_S}\right)^2 \cdot k \qquad (1)$$

4.5 Cavitating Propeller

Given a ship wake field, the cavitation inception of a propeller depends on a number of quantities such as turbulence, nuclei content, Reynolds number in case of vortices and the value and variation of the non-dimensional hydrostatic pressure over the propeller disc. Reviews on cavitation inception are given by Rood (1991) and van Rijsbergen (2016).

The influence of free-stream turbulence on cavitation inception and radiated noise has been shown by Korkut (1999) and Korkut and Atlar (2002). The influence of the nuclei (air) content on cavitation inception is discussed in detail by the 23rd ITTC Specialist Committee on Water Quality and Cavitation (2002). The related similitude number is the Weber number which at model scale is different from ship scale. Lack of (adequate size) nuclei leads to a delay in inception. The influence of water quality on cavitation inception at ship scale is usually negligible due to the large size, high speed and sufficient nuclei. At model scale however, water quality is an important factor but it strongly depends on the facility and each facility has developed its own procedures to minimize this influence.

One of the most important similarity parameters related to cavitation is the cavitation number which specifies the non-dimensional pressure threshold above vapour pressure. Ideally, identical cavitation numbers should yield identical cavitation patterns in model scale and in full scale. However, the variation of the hydrostatic pressure in the propeller disc is only identical if the Froude number (based on propeller diameter and tip speed) is identical. As Froude number identity is not satisfied in cavitation tunnels, the cavitation number identity can only be satisfied for one specific location in the propeller disc for which usually the location of maximum cavity extent is selected in the top of the propeller disc. Additional corrections to the cavitation number are sometimes applied to correct for other effects such as stern wave height or other empirical information.

Vortex cavitation at and near inception is influenced by the Reynolds number as the pressure in the core of the vortex is influenced by the Reynolds number, McCormick (1962). This change in pressure leads to a delay in cavitation inception as expressed by the scaling rule

$$\frac{\sigma_{i,s}}{\sigma_{i,m}} = \left(\frac{\mathrm{Re}_s}{\mathrm{Re}_m}\right)^m \qquad (2)$$

A typical value for m is 0.35, 21st ITTC report. Shen et al. (2009) provide a formulation for m that is dependent on Reynolds number. Strasberg (1977) suggests that cavitation tests should be performed at equal value of σ/σ_i while Blake (1986) and Baiter (1992) suggest other relations. Oshima (1990) finds good correlation of the radiated noise of a cavitating tip vortex between model scale and full scale if the model scale cavitation number is reduced with respect to the full scale cavitation number. Expressing the ratio between the two cavitation numbers as the ratio of Reynolds numbers for cavitation inception, a value of m = 0.15 is found. Bosschers (2009) shows that for an analytical solution of a 2-D cavitating vortex that the cavity size is independent of Reynolds number when the cavity size is much larger than the viscous core size. Model tests can then be performed at cavitation number identity. Analysis of the formulation shows that near inception the cavity size scales with the ratio $\sqrt{\sigma_i-\sigma}/\sigma_i$ which was one of the scaling relations proposed by Baiter (1992). Results for the vortex cavity radius r_c are presented in Figure 5 for different values of the viscous core size r_v

representing different Reynolds numbers. The vortex cavity model can be used to obtain similar cavity sizes in model tests and full scale tests if the cavitation number at inception is known.

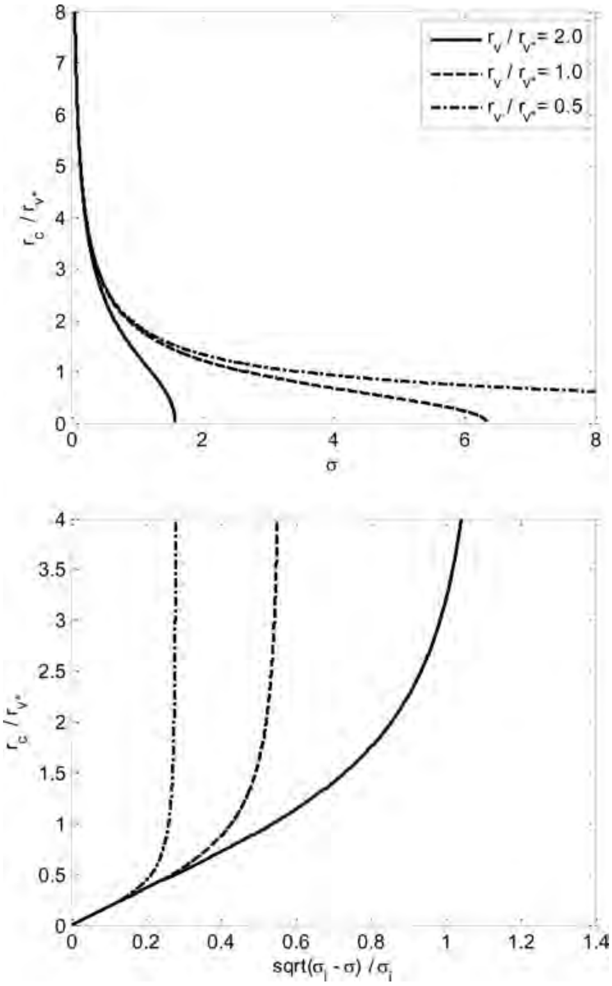


Figure 5 Influence of vortex viscous core radius on vortex cavity radius using the formulation by Bosschers (2009) showing the scaling for large cavity size (top) and small cavity size (bottom)

4.6 Acoustic Aspects

Noise Scaling. The formulations for the scaling of cavitation noise from model scale to full scale can be reduced to the two formulations as originally suggested by Levkovskii (1968) and Strasberg (1977). Strasberg uses similarity parameters assuming that the collapse is dominated by inertia effects. Levkovskii relates the radiated acoustic energy to the total energy of the collapsing bubble assuming constant acoustic efficiency caused by a shock-wave type collapse. When the acoustic efficiency is a linear function of Mach number, a similar formulation as Strasberg is obtained, see Baiter (1985). It is suggested that the Strasberg formulation is more appropriate for ‘low frequencies’ while the Levkovskii formulation is more appropriate for the ‘high frequency’ region where the spectral shape falls off with a f^{-2} slope. Unfortunately, no criterion is available for the transition frequency region. Results of the questionnaire by the 28th ITTC show that both formulations are in use. Discussions and formulations for cavitation noise scaling are given by Løvik (1981), Bark (1985), Blake (1986).

In the ITTC 1987 report scaling relations are given as

$$\begin{aligned} \Delta L_{sm} &= 20\ \log_{10}\left\{\left(\frac{\sigma_s}{\sigma_m}\right)^w \left(\frac{r_s}{r_m}\right)^x\right\} \\ &+ 20\ \log_{10}\left\{\left(\frac{D_s n_s}{D_m n_m}\right)^y \left(\frac{D_s}{D_m}\right)^z\right\} \end{aligned} \qquad (3)$$

where the difference in density and speed of sound has been neglected. In the above, the subscripts s and m refer to the ship and model respectively, r is the reference distance for which the noise level is predicted, D is the propeller diameter, σ is the cavitation number, n is the propeller rate of rotation. The values of the exponents are given in Table 3 for proportional (i. e. 1/3 octave) bandwidth and Table 4 for constant (i.e. 1 Hz) bandwidth.

Table 3 Exponents for noise scaling valid for proportional bandwidth

formulation	w	x	y	z
‘high frequency’	0.5	1.0	1.5	1.0
‘low frequency’	1.0	1.0	2.0	1.0

Table 4 Exponents for noise scaling valid for constant bandwidth

formulation	w	x	y	z
‘high frequency’	0.25	1.0	1.0	1.5
‘low frequency’	0.75	1.0	1.5	1.5

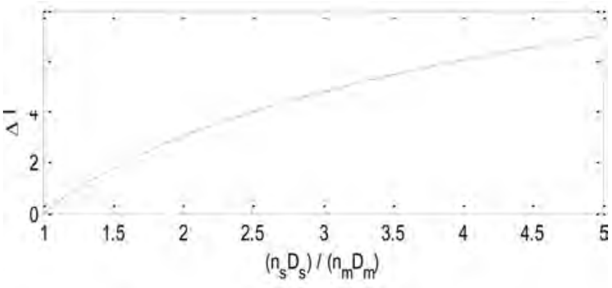


Figure 6 Difference in noise level between y = 2.0 and y = 1.5 in eq. (3)

The equation for the scaling of the frequency is identical for the two formulations and is derived from the time scale of the Rayleigh time for the collapse of the cavity:

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}\sqrt{\frac{\sigma_s}{\sigma_m}} \qquad (4)$$

The difference in propeller tip speed (πnD) scales differently for the low and high frequency formulation. Figure 6 shows the difference in noise levels for the two formulation in proportional bandwidth. A difference in full scale noise levels of six dB is obtained when the ratio of full scale and model scale tip speeds is four.

The scaling of the hull pressures is easily obtained from eq. (3) as the distances now scale with propeller diameter. As the harmonics at blade passage frequencies of the hull pressures scale with the tip speed squared, it is concluded that hull pressure tonals scale according the ‘low frequency’ formulation when presented in proportional bandwidth.

It is remarked that the cavitation number in equation (3) and (4) is related to the acoustic efficiency only and that the relation assumes that the cavity length and dynamics is similar for model scale and ship scale. Normally, model tests are performed at identical cavitation number as ship scale and no correction is required.

Noise radiation by cavitation was assumed to depend on the behaviour of a single (cavitation) bubble following theoretical studies of bubble dynamics (Fitzpatrick, 1958). According to this approach, spectral power density of a set of bubbles becomes the product of the number of bubbles per unit time and spectral energy density due to the growth and collapse of a single bubble. However, the single bubble approach fails at very high bubble densities. Van der Kooij (1986), Arakeri and Shanmuganathan (1985) and Yu et al. (1995) have supported this conclusion.

5 REVIEW OF THEORETICAL AND NUMERICAL PREDICTION METHODS

The propeller represents an important source of underwater noise, especially in the presence of some cavitation phenomena (Carlton 2007). In the last decade, there has been a growing interest toward the numerical prediction of propeller noise in order to comply with regulations on passenger comfort, acoustic sea pollution and to enhance a vessel’s stealth and operational capabilities. Propeller noise can be predicted through well-assessed aeroacoustic formulations developed and validated during the last three decades in aeronautics and widely-used for the analysis of the aerodynamically-generated noise from rotary-wings.

Some of the aspects on underwater noise prediction methods are discussed in the following sections providing the *state of the art* for the numerical prediction methods of propeller noise. Specifically, Section 5.1 presents an overview on the hydrodynamic approaches currently used to detect the hydrodynamic sources of sound for cavitating/noncavitating propellers; Section 5.2 deals with the Acoustic Analogy, discussing the role of volume terms in noise prediction; Section 5.3 proposes the most relevant empirical methods whereas in Section 5.4 the unified hydrodynamic/hydroacoustic formulation for potential flows is briefly summarized. Noise radiation in bounded space in the presence of the hull, is discussed later in

Section 6.2.

5.1 Hydrodynamic Sources of Sound

Non-cavitating Propellers. The physical aspects of non-cavitating propeller noise are discussed in Section 4.4. With the increasing capability of computer technology, numerical prediction methods for non-cavitating propeller noise have made great progress in recent years. Most of the methods couple the Computational Fluid Dynamics (CFD) simulations, such as Unsteady Reynolds Averaged Navier-Stokes equations (URANS), Large Eddy Simulation (LES) or their hybrid methods, for turbulent flow simulations, and Ffowcs Williams-Hawkings (FWH) equations or its variations for acoustical analogy. For noise predictions, LES or hybrid RANS-LES method simulations can capture more detailed vortex structure and turbulent flow field detail than the URANS method (Ianniello, 2016, Nitzkorski and Mahesh 2016). As a result, the URANS method cannot predict the broadband noise from a flow field. With the LES and hybrid methods, reasonable results are obtained in broadband noise predictions compared with the experiments in model scale (Chen and Liu, 2016, Özden et al., 2014).

The tonal noise from non-cavitating propeller can be predicted either by using the potential flow assumption or by solving the full set of viscous flow equations (Navier-Stokes equations) by means of CFD. The lifting surface and Boundary Element Method (BEM) can be used to solve the tonal noise with the potential flow assumption, e.g. (Su and Kinnas, 2015, and Greco et al., 2014).

There is a vast amount of literature about propeller flow predictions calculated by the URANS method. However, accurate prediction of tip vortices and the wake field is still demanding. The grid sensitivity studies and the influence of different turbulence closures on the turbulent structures modeling in the propeller slipstream has been investigated, e.g. in Yang et al. (2014), Yakubov et al. (2013), Sipilä et al. (2014), and Viitanen et al. (2017). Yamada and Kawakita (2015) used the Embedded Large Eddy Simulation (ELES) method to predict the shedding of unsteady vortices at the trailing edge of a blade section profile. Abbas et al. (2015) simulated the hull-propeller combination by the RANS method and a Delayed Detached Eddy Simulation (DDES) method. The inhomogeneous ship wake predicted by the DDES was significantly higher than that modeled by the RANS.

Regarding the use of computational methods to predict noise source levels from propellers, the convergence of quantities affecting on the noise sources, such as the Lighthill tensor, should also be evaluated.

Cavitating Propellers. The cavitation models used in engineering CFD simulations can be divided into barotropic models, where the vapour volume fraction is calculated from the barotropic equation of state, and used in the Euler-Euler and Euler-Lagrangian models. The phase change in Euler-Euler models advances by a source term in the transport equation. Examples of widely used Euler-Euler models are the ones presented by Kubota et al. (1992), Singhal et al. (2002), Zwart et al. (2004), Merkle et al. (1998), and Kuntz et al. (2000). In the Euler-Lagrange models cavitation nuclei are seeded into the flow field. The motion, deformation, and growth and collapse of the bubbles are calculated from the surrounding field properties. Yakubov et al. (2013) and Ma et al. (2015) studied the Euler-Lagrange approach in their simulations of dynamics of cavitating flow structures. The validation of the simulations showed good agreement against the tests as reported by the authors.

As in the non-cavitating flow conditions, the LES methods solve the turbulent structures more detailed compared to the RANS method. The cavitating flow structures on hydrofoils, wedges, and propellers have been studied by the LES method by Li et al. (2015), Gnanaskandan and Mahesh (2016), and Lu et al. (2014), respectively. The LES method seems to solve the cavitating flow structures and their dynamics qualitatively well in different problems based on comparison to experiments.

Experimental data for a propeller benchmarking case was made available by SVA Potsdam under the acronym PPTC (Potsdam Propeller Test Case). It concerns a propeller in wetted and cavitating conditions at 12 degree inclined inflow condition. This has been simulated by a number of organizations using different CFD and BEM codes, and varying cavitation models, in a workshop held in the symposium of marine propulsors (smp'15). The results are reported in Kinnas et al. (2015). In general, it can be concluded that the global performance characteristics calculated by the CFD methods were relatively close to other CFD results and to the measurements. The divergence was higher among the panel methods. The tip vortex cavitation was not well predicted due to the low grid resolution in the tip vortex location in many CFD simulations. The pressure pulses emitted by the propeller were investigated experimentally and numerically by shifting the propeller close to the wall in the cavitation tunnel. There was large deviation in the pressure pulse levels emitted by the non-cavitating and cavitating propeller between the simulations and the measurements. Due to the very small gap between the propeller tip and the wall, the studied cases were very complex.

5.2 Propeller Noise Prediction by the Ffowcs Williams and Hawking Equation

The form of the Acoustic Analogy mostly proposed for the prediction of noise from moving bodies is based on the solution of the Ffowcs Williams-Hawkings (FWH) (Ffowcs Williams and Hawkings, 1969) acoustic analogy formulation that has proven to be an effective, reliable numerical tool for sound radiation problems dominated by fluid/body interactions (K.S. Brentner, F. Farassat, 1998, 2003). It is a rearrangement of the Navier-Stokes Equations for compressible flows written in terms of a nonhomogeneous wave equation where the forcing terms that account for the main sources of sound are due to the kinematics of the body (thickness noise), the unsteady pressure fluctuations upon the emitting body surfaces (loading noise) and the flow-field sources described by the Lighthill Tensor (quadrupole noise). Mathematically, the solution of the FWH equation is obtained through Boundary-Field Integral Formulations yielding contributions due to thickness, loading and quadrupole sources localized in the flow field around the body (Farassat and Brentner, 1988). However, for hydroacoustic investigations where the main hydrodynamic sources of noise may be assumed localized on the body surface, Boundary Element Method (BEM) techniques may be applied. This avoids cumbersome volume integrations (Farassat 2007). It is remarked that Farassat and co-authors have developed several formulations to solve the FWH equation but for helicopter rotor and aircraft propeller noise where volume terms may be neglected the formulation 1A is preferred (Farassat 2007).

The massive literature on hydroacoustics developed during the last years shows how; i) the FWH is applied, or ii) computational results are obtained for the linear contributions given by thickness and loading noise terms, or iii) including the nonlinear terms by the direct volume integration of the quadrupole source, or iv), and last (but not least), using the so-called *permeable* FWH approach (P-FWH). The P-FWH allows overcoming the need of volume integrations and, in principle, to determine the hydroacoustic behaviour of complex multibody configurations, as fully-appended hulls with propellers.

Linear Hydroacoustics. Some important guidelines on the more correct use of the FWH may be carried out looking at the investigations addressed by Ianniello (2013, 2014, and 2015) on the role of volume terms in the hydroacoustic analysis of marine propellers working in open water or complete scaled ship model in steady course. For the configurations and (non-cavitating) operating conditions studied, such papers show that the acoustic contribution from the linear terms seem to be circumscribed to a very limited spatially region, in that, moving far from the emitting body, pressure fluctuations rapidly reduce, appearing substantially related to nonlinear sources of sound such as vorticity and turbulence, regardless of the blade rotational speed. Even though preliminary, this result suggests that, from a practical standpoint, the hydroacoustic analysis of noncavitating propellers in open water or in behind-hull conditions should be performed by the 1A Farassat formulation whenever the interest is on the prediction of the tonal noise generated by: i) unsteady blade pressure distributions and wake-vorticity downstream; ii) impulsive noise due to blade-wake impacts; iii) operating conditions within velocity fields induced by (other) lifting surfaces. Within these applications, the loading noise term dominates the overall noise signatures in the near field surrounding the propeller and in the mid field extending a *few* diameters far from the propeller tip. To quantify *a priori* a range of distances within which the linear terms dominate the underwater noise is not possible because a value of *admissible distance* depends on the operating conditions, that is: i) unsteadiness of the blade pressure distribution; ii) its impulsive character occurring in presence of impacts between the rotor disk and vortical structures; and, iii) the local high-frequency changes, both in time and space, of the inflow velocity to the propeller blades.

In order to give an order of magnitude, in the case-study investigated in Ianniello (2013), the *admissible distance* is more or less two diameters from the blade tip. Thus, within the limits of the above considerations, neglecting quadrupole terms becomes acoustically admissible and the 1A Farassat formulation still remains reliable. Note that the evaluation of hull pressure-fluctuations induced by propellers falls within this range of applicability. For modelling these working conditions, three-dimensional (3D), unsteady, free-wake panel methods, as well as two-dimensional, unsteady airfoil formulations, such as Sears, Theodorsen and Küssner-Schwarz theories, may be used to detect the hydrodynamic sources of noise governing the loading noise term. In this framework, Gennaretti et al. (2012) proposed a novel hydroacoustic formulation, in the frequency-domain, to identify spectrum and directivity of the emitted noise starting from the knowledge of blades pressure, propeller motion and inflow disturbances (if present), in terms of their harmonic components, particularly suitable for active noise control purposes. Further, Bernardini et al. (2016) developed a compact-sources hydroacoustic approach for the prediction of the tonal noise induced by propellers in manoeuvring, by transforming the 1A Farassat formulation into an integral-spectral representation that allows the enhancement of the computational efficiency of the hydrodynamic/hydroacoustic solvers associated with a reduction of the amount of data exchange.

In Wei et al. (2016) the non-cavitation noise caused by a propeller running in the wake of a fully-appended submarine, including scattering effects, is analyzed. CFD provides the fluctuating pressure on the propeller blades whereas the linear terms of the FWH yield the underwater noise signature. For *admissible* distances ranging from two to two-hundred diameters, the importance of submarine's scattering effect in evaluating the propeller non-cavitation noise is highlighted.

Other applications where the use of thickness and loading noise terms yield reliable predictions of the radiated noise concerns with sheet cavitation noise, typically affecting propellers working in the wake of the hull (Carlton 2007); as shown in Seol et al. (2005), Seol (2013), Salvatore, Ianniello (2003) and Ianniello (2015). The induced-noise from the dynamic of attached bubbles of vapour may be modeled by computing the acoustic integrals of the 1A Farassat formulation by a step-by-step procedure where an *equivalent* blade shape is defined at each azimuthal position to account for the time-varying cavity occurrence. To this aim, unsteady 3D BEM hydroadynamics, coupled with reliable sheet cavitation models, is well suited for detecting the time-varying cavitation pattern in terms of inception, growth and collapse, as shown by Pereira et al. (2004, 2016) and Salvatore et al. (2006). Note that in presence of sheet cavitation, the distances up to which linear terms dominate the underwater noise are greater than for the noncavitating cases, depending on the dynamic behaviour of the transient cavitation in terms of formation, growth and implosion of the bubbles of vapour.

Inclusion of Nonlinear Sources of Sound. Following the numerical results first carried-out by Ianniello (2013), the nonlinear hydrodynamic sources of sound, localized in the flow-field around the propeller, play a crucial role in the noise generation mechanism. As shown, the direct solution of the FWH by Boundary-Field Integral Formulations is mandatory to yield hydroacoustic signatures in agreeement with CFD (Computational Fluid Dynamic) computations, here performed by RANS solvers. In this context, the inherent lack of compressibility effects in hydrodynamic CFD codes does not impair the generality of the conclusions because the far field involves observation points at a few diameters from the propeller tip so the change in time-delay due to compressibility is negligible. However, the need of accurately modelling the velocity field in an extended flow region around the propulsor(s) dominated by massive turbulence and vorticity, makes the direct evaluation of the nonlinear terms an onerous and unfeasible task. To overcome this drawback, the solution of the porous FWH, as proposed by Di Francescantonio (1997), has been applied, yielding a very good agreement with RANS results, in terms of pressure signatures and proving its effectiveness and reliability to characterize propeller hydroacoustics. Similar conclusions are drawn by Ianniello (2014) concerning the analysis of underwater radiated noise by a scaled complete ship model in steady conditions. Note that CFD solvers allow for detection of hydrodynamic sources of broadband noise, not modeled by potential flow approaches which are limited to the tonal noise components only.

Cavitation Noise Prediction. A few examples of cavitation noise prediction are discussed next. Hallander et al. (2012) show comparison between full scale measured cavitation noise levels and results from various computational methods including a coupled unsteady RANS and P-FWH solver. These computations clearly show that this approach can predict tonals at harmonics of the blade passage frequency but underpredicts broadband levels. Kellett et al. (2013) proposed the P-FWH coupled with an unsteady RANS solver to study the underwater noise signature emitted by a ship. The role of the free-surface in terms of noise is discussed, showing that above 200 Hz it may be neglected.

Lloyd et al. (2015), proposed an investigation on the predictive capabilities of the P-FWH respect to RANS pressure solutions. An important conclusion of this work concerns the need of a well-converged accurate hydrodynamic solution for a correct use of the P-FWH.

Lidtke et al. (2015) applied the P-FWH together with a mass transfer cavitation model by Sauer & Schnerr coupled to an unsteady RANS simulation to predict marine propeller noise signatures. Results indicate that such an approach provides the means for identifying low-frequency noise generation mechanisms in the flow, but does not allow for the fine-scale bubble dynamics or shock wave formation to be resolved.

In Hynninen et al. (2017), the prediction of sound from a cavitating marine propeller in a cavitation tunnel is addressed. Propeller noise is computed by using URANS simulations and finite element method a (FEM)-based acoustic analogy. Numerical results highlight the strong impact of the blade passing frequency and its harmonics on the sound pressure level as well as the role of the wake field a source of noise in a wide frequency range.

Challenges. As discussed in Section 5.1, the RANS methods are unsuitable to predict broadband noise from propellers due to their time-averaging nature in modeling the turbulent fluctuations and introducing too much dissipation in the flow field. For practical applications, LES is too expensive in required computing power. Therefore, the use of hybrid RANS-LES methods offers an attractive alternative to detect the hydrodynamic sources of noise for the further use into the P-FWH. Despite numerous studies published, no consensus emerges from the literature on how to implement and use a permeable surface in P-FWH solver. The question of the treatment of the downstream end of the FWH surface is a prime example of the type of debates related to the use of a FWH solver. This issue is known as the *end cap* problem. When closed surfaces are used, spurious noise is generated by the passage of turbulent eddies through the downstream end, which is compensated by the volume term in the exact FWH integration. Thus, using open surfaces at the downstream end would reduce the error related to the omission of this volume term. However, open surfaces introduce their own errors: data is not recorded on a portion of the surface and more importantly, truncation of the surface generates artificial spurious noise. The question of which errors spoil the results most is not yet resolved. The reader is referred to Nitzkoskiri (2104) and Mendez et al. (2013) to get relevant but preliminary details on this topic.

5.3 Other Noise Prediction Methods

In the framework of potential flow theory, the tonal noise field generated by propellers may be computed through a unified hydrodynamic and hydroacoustic formulation where the Bernoulli equation is used as a hydroacoustic solver. Such an approach requires first the solution of the hydrodynamic problem: to this aim a boundary integral equation is solved to evaluate the velocity potential field upon propeller surfaces and further the corresponding integral representation for the potential yields the potential distribution everywhere in the field. Finally, the Bernoulli equation gives the corresponding acoustic pressure. Such a methodology is applied by Salvatore et al. (2009) to compute non-cavitating and cavitating noise of propellers operating in a wake field. Comparisons with the FWH results confirm the goodness of the acoustic predictions performed. Note that acoustic effects induced by the vorticity field emitted by the blades are directly computed by integrating the potential jump across the wake surface without the need of volume terms.

Along with the study on FWH or other CFD method, empirical or semi-empirical approaches with some theoretical consideration have been discussed. Although these methods model limited parts of phenomena, they are utilized especially in an initial design stage as many of them require less computational cost compared to other detailed approaches.

Most simplified approaches for very initial prediction utilize fully empirical formula based on curve fitting to measurement data. As one example of this approach, Wittekind (2013) attempted to describe noise level using mechanical and geometrical parameters. In this study, relatively simple equations using principal ship particulars like block coefficient, displacement etc. have been proposed for prediction of broadband noise from propeller and machineries.

Other approaches are semi-empirical ones with theoretical considerations. Typically they have two different strategies for the two noise components, i.e. the tonal noise and the broadband noise. The tonal noise is blade rate and its harmonic components, and the main source is assumed to be the variation of cavitation volume. Because the size of this cavitation on the propeller seems to be much smaller than the wave length in tonal noise frequencies, Okamura et al. (1988) uses a monopole model to deal with this component, and utilizes propeller lifting surface method with the bubble tracing method based on the Rayleigh-Plesset equation, for obtaining the cavitation volume change. Also the lifting surface and BEM approaches with sheet cavitation models, which assume the pressure inside the cavity is the constant vapor pressure, can predict the tonal noise caused by sheet cavitation. Different methods have been utilized to model the closure of sheet cavitation.

For broadband noise, one approach based on a semi-empirical equation has been proposed by Brown (1976). Brown has proposed a simple equation which describes the upper limit of broadband noise with mid frequency range (abt. 100 Hz to 10 kHz) based on measurement data for thrusters. In addition he adds a term A_c which describes the swept cavitation area in the propeller disc. Based on this study, several utilizations or modifications of his equation have been proposed. For example, Okamura et al. (1988) applied a prescribed lifting surface method (LSM) to predict A_c. The application of LSM is also seen in Ekinci et al. (2010) and Takinaci et al. (2013). Here Takinaci et al. used a modified equation adding a term representing tip vortex cavitation, using its inception speed. Another example of prediction of A_c is shown by Yoshimura et al. (2004). They adopted Brown's equation for the initial design of a research vessel, and the A_c was estimated using Burrill's chart, which is an empirical chart describing the relation among the thrust load, cavitation number and A_c.

As another approach for the broadband noise, Matusiak (1992) proposed a theoretical method modeling bubble collapse of free bubbles from sheet cavitation. He modeled the number and mean size of cavitation bubbles generated by a break-off of the unsteady sheet cavitation, and calculated the noise level using bubble dynamics. Kamiirisa et al. (2005) adopted this idea, and estimate the behavior of sheet cavitation using LSM or model test. From the thickness of the aft end of sheet cavitation, they assumed the number and its radius distribution with a β-function. They also introduced the effect of compressibility and damping in bubble flow to improve the prediction accuracy. Ando et al. (2016) replaced the LSM in Kamiirisa et al. for a RANS CFD. This type of approach has been also adopted by Lafeber et al. (2015) and Veikonheimo et al. (2016). They adopted BEM for estimation of sheet cavitation, and bubble oscillation equation noise prediction. The results with their approach was compared and discussed with the result from Brown's equation.

To deal with other sources than sheet cavitation, Yamada et al. (2015) studied the noise from tip vortex cavitation. In their study, the pressure profile in a tip vortex was estimated using vortex strength from LSM, and vortex core size from boundary layer calculation. From this information, bubble behaviour in tip vortex cavitation and its noise was calculated with bubble dynamic equation by Rayleigh-Plesset, and summed with other broadband noise from Brown's equation. Bosschers (2017) combined semi-empirical vortex model and BEM to predict the vortex cavity size, and used it to predict the hump-shaped pattern for the spectrum. The center frequency and level of this hump is described with an empirical model which is obtained from the database of model scale and full scale measured hull pressure data. This empirical model is a function of among others the cavity size, e.g. propeller diameter, number of blades, cavitation number, etc. Also, a BEM method can be adopted to predict the fluctuation of tip vortex cavitation using some simplified vortex model such as a Rankine model and e.g. the Rayleigh equation. Kanemaru and Ando (2015) included a super cavitation model to the propeller tip region in order to improve the accuracy of the higher order frequency fluctuations emitted from the tip vortices. Wang et al. (2016) studied the prediction of tip vortex cavitation inception with a low-order panel method. They developed a smoothing parameter that was used to simulate the roll-up process of the propeller wake. Good agreement between the propeller wake shape calculated by the panel method and by the RANS method was achieved. The tip vortex cavitation inception was predicted by summing up the circulation of the wake panels at the tip vortex region and solving the Burgers vortex model based on the axial circulation distribution and the viscous core radius.

In some cases, RANS CFD is used to calculate the nominal or effective wake field as input to the BEM or other prediction method, as the CFD methods are expensive when simulating the hull-propeller interaction. Lafeber et al. (2015) and Firenze and Valdenazzi (2015) used this approach. Veikonheimo et al. (2016) have calculated the propeller noise using a combination of the BEM and semi-empirical methods.

The comparisons between the results from these empirical or semi-empirical approaches and measurement data in model or full scale have been presented in several papers. Some results show relatively good agreement between prediction and measurement, but some discrepancy are found in other papers even though both predictions are based on a similar approach. From this situation, it is still difficult to provide quantitative conclusions on the utility of these approaches.

6 PROPAGATION

6.1 Introduction

Sound propagation in the ocean is a complex phenomenon which depends on the frequency range of the noise source, bathymetric conditions, sea state, and geoacoustic properties of the bottom sediments. In most of the cases, many of these parameters are not well known.

The sound speed in water depends on the temperature, salinity, and pressure. The sound velocity increases with increasing temperature, salinity and pressure (e.g. Urick, 1983). These parameters typically change vertically in the seas rather than laterally. The influence of gas bubbles on the sound speed is usually not taken into account.

The sound paths travelling in the seas can be prescribed by Snell's law, i.e.

$$\frac{\cos\theta}{c(h)} = \mathrm{const} \tag{5}$$

where θ is the acoustic ray angle with respect to the horizontal direction, and $c(h)$ is the local sound speed as a function of depth h. This relationship states that the acoustic paths tend to bend towards the lower sound speed.

In deep seas outside the polar region the water near the surface is warmest. Due to the mixing effects of waves and wind, the temperature is nearly constant in the surface layer. In a mixed surface layer the sound velocity increases with depth due to the constant temperature and increasing pressure. The depth of the surface layer can vary from about ten meters to few hundred of meters depending on the sea state and the region (e.g. D'Spain et al., 2006, and Jensen, 2011).

Below the surface layer there is a thermocline, in which the temperature decreases gradually with depth and thus also the speed of sound decreases with depth. Below the thermocline there is a deep isothermal layer, in which the speed of sound increases with depth due to the increasing pressure. The lowest sound velocity is in the thermocline at about 1000 meters depth at mid-latitudes (e.g. Jensen et al., 2011). This minimum velocity depth forms an axis around which the sound paths bend by refraction without losses from surface and/or bottom reflections and diffractions. This phenomenon forms the so-called deep sound channel.

Sound paths/rays can also be captured in surface ducts, in which the sound paths travel by a surface reflection-refraction manner. If the surface layer temperature is layered and the warmest water is at the top, the sound paths at the surface duct can propagate without surface reflections.

To be captured into the propagation ducts, the sound paths must encounter the ducts at a relative low angle. The critical angle depends on the source location and bathymetric conditions of the sea, see e.g. Urick (1983) or Jensen (2011). The sound paths with steeper angles travel across the ducts and hit the sea surface and bottom. The surface duct has a lower frequency limit in which it can propagate, i.e. similar to a cut-off frequency as in shallow waters. Urick (1983) gives a rule of thumb on determining the cut-off frequency based on radio wave propagation in an atmospheric duct: $f_{min} = \frac{0.398}{\sqrt{g}}\left(\frac{c}{D}\right)^{\frac{3}{2}}$, where the parameter D [m] refers to the critical depth of the mixed surface layer, c [m/s] to the sound speed and g [s^{-1}] to the vertical gradient of the sound speed.

In shallow waters (depth < 200 m, e.g. Etter, 2009) the deep water sound channel is obviously absent. In summer periods in shallow waters, the sound paths tend to bend downwards to the bottom due to warm water at the surface. In the winter period, the water is more isothermal and the sound paths travel more straight. The propagation losses in winter are lower due to less interaction with the bottom.

In the arctic regions in the winter period the coldest water is at the sea surface or below the ice cover. As a result, the whole water domain has increasing temperature towards bottom. The sound paths tend to bend upwards over the whole water depth.

Part of the acoustic energy is continuously absorbed into heat when sound propagates in water. Additionally, acoustic energy is scattered by inhomogeneities in water. The volume attenuation is contributed both by absorption and scattering. The volume attenuation in water is frequency dependent. Sound attenuation in sea water (salinity of 35 ppt and *p*H of 8.0) is about 10 dB over a distance of about 2200 km at 100 Hz, 145 km at 1 kHz, and 9 km at 10 kHz (Jensen et al., 2011). The salinity and acidity of sea water affects the attenuation of the volume. In fresh water, the sound attenuation is several magnitudes lower than that in sea water.

6.2 Aspects of Noise Propagation

Near Field-Far Field. The differences in sound propagation in near field and far field might be considered when dealing with noise measurement at model scale. Assuming that we are in free field environment, the pressure wave have different propagation behavior in the near field and the far field. In the near field, there is no simple relationship between sound level and distance. The sound pressure level does not obey to the inverse square law of the distance and the particle velocity is not in phase with the sound pressure. In the far field, the sound pressure level obeys inverse square law of the distance (the sound pressure level decreases 6 dB with each doubling of distance from the source). Also, in this region the sound particle velocity is in phase with the sound pressure.

The boundary between the near field and

the far field is dependent on the type of source (monopole, dipole, quadruple or multi-pole) and on the size of the sound source. In the case of a monopole source, the boundary is of the order of magnitude of the radius of the pulsating sphere. It is remarked that the pressure due to a pulsating sphere or monopole has no near field contribution (in contradiction to the velocity) which implies that the pressure measured close to a monopole corresponds to the acoustic pressure. A cavity collapse that is very localized in space and time can be interpreted as a monopole and the noise measurements can therefore be made rather close to the cavity as long as cavitation noise exceeds other noise sources. The far field cavitation noise is predicted from near field (hull) measurements by Foeth and Bosschers (2016).

Hull Scattering. Underwater acoustic scattering from the hull may modify the directivity and magnitude of propeller noise with respect to the operating conditions in unbounded space. Hull scattering is characterized by the Helmholtz number, which is the product of the wave number and the characteristic size of the object.

Kao and Kehr (2006) proposed a time-domain iteration method for computing multi-frequency scattering waves from underwater obstacles. This method, written in terms of velocity potential, is characterized by an iteration process in the time domain that can converge robustly for a body with arbitrary shape, even with multiple sharp edges.

In Kehr and Kao (2011) the same scattering modeling, written in terms of total pressure, has been applied to evaluate the pressure fluctuation on the ship hull and underwater acoustic field outside the ship hull induced by the unsteady sheet cavitation of a real propeller operating behind a container ship, including the presence of sea surface by the image techniques.

Starting from the works of Vaz and Bosschers (2006) and van Wijngaarden (2006), a mathematical method for the determination of propeller-induced hull-pressure has been proposed. Propeller sources of noise, described in terms of strengths of sets of ‘ring sources’ of monopole and dipole type, are the input of the scattering modeling based on a Boundary Element Method for the acoustic potential satisfying the Kirchhoff-Helmholtz integral equation. A detailed dissertation on the capabilities of this approach are documented in van Wijngaarden (2011).

In Testa et al. (2010, 2015), acoustic scattering effects are computed, in the frequency domain, by a nonconventional use of the Ffowcs Williams Hawking Equation. The formulation, well suited to account for structural vibrational effects (if present) yields predictions in very good agreement with those obtained by solving, hydrodynamically, propeller(s) and hull jointly through a 3D unsteady panel method.

Thus, the literature concerning sound scattering problems highlights that the scattered pressure field is typically predicted through linear approaches based on: i) boundary integral formulations solving the Helmholtz equations for the velocity potential or the acoustic pressure; ii) non-standard, frequency-domain boundary integral solution of the linear version of the Ffowcs Williams and Hawkings equation (FWH), that extends the use of the acoustic analogy to scattering problems. Applying Boundary Element Methods (BEM), these linear formulations yield the pressure field upon the scattering body surface through solution of a boundary integral equation, whilst the noise scattered in the fluid domain is then evaluated by the corresponding boundary integral representation.

In Gennaretti et al. (2016) it is shown that Helmholtz formulations (for pressure and velocity potential) and the linear FWH formulation provide fully equivalent results, as long as the scattering body is at rest. However, relevant discrepancies arise when the body moves: the higher the Mach number, the more relevant are the discrepancies among outcomes given by these three linear approaches. Observing that with the viscosity effects ignored, these formulations are all based on the same flow modelling assumptions, the discrepancies have to reside in the different influence of the neglected nonlinear terms.

Lloyd-Mirror Effect. For a submerged noise source such as a cavitating propeller, the reflection of sound by the sea surface creates an interference pattern that is referred to as the Lloyd mirror effect. For a monopole noise source a simple formulation can be found for the total received pressure minus the direct contribution of the source, referred to as propagation loss correction factor or Transmission Anomaly (TA) by Urick (1979). The loss factor can be given as a function of distance r between source and receiver or frequency f:

$$\begin{aligned}\Delta PL &= 20\log_{10} \| 1 + K\exp\left[-i\pi\frac{r_0}{r}\right] \| \\ &= 20\log_{10} \| 1 + K\exp\left[-i\pi\frac{f}{f_0}\right] \|\end{aligned} \tag{6}$$

with $r_o = 4hdf/c$ and $f_0 = cr/4hd$, with d the source depth, h the receiver depth and c the speed of sound. The parameter K is the reflection coefficient with K = -1 for a flat sea surface. The propagation loss is presented in Figure 7. The interference patterns at high frequencies disappear in the presence of a rough free surface of which a reflection coefficient is given by $K = \exp(-2k^2\sigma^2\sin^2\theta)$ with K the wave number σ the rms wave roughness height and θ the depression angle, Clay & Medwin (1977). At high frequencies K approaches zero. Ainslie (2010) gives the following formulation for the propagation loss:

$$\Delta PL = -10\log_{10}\left(\frac{1}{2} + \frac{1}{4k^2d^2\sin^2\theta}\right) \tag{7}$$

which leads to ΔPL = 3dB at high frequencies.

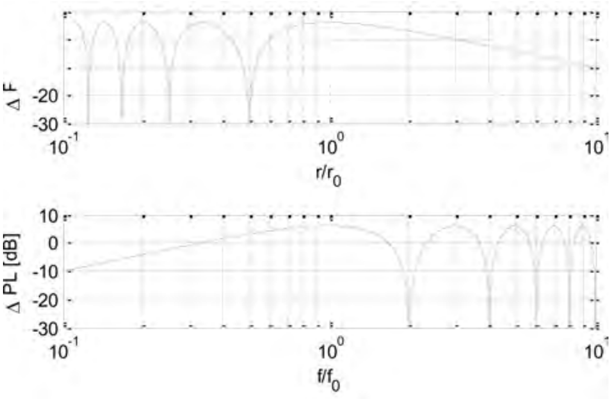


Figure 7 Variation of the propagation loss correction factor due to Lloyd mirror for a flat sea surface with distance (top) and frequency (bottom)

Influence of Sea Bottom. The sea bottom is acoustically a lossy boundary. Sound propagation in shallow water is dominated by bottom reflection loss at low and intermediate frequencies (< 1 kHz), and by scattering losses at higher frequencies, e.g. Jensen et al. (2011). The noise reflection and scattering from the sea bottom depends highly on the seabed shape and its geoacoustic properties. The bottom reflection loss varies with the grazing angleφ, which is the angle between the sea bottom and the receiving sound ray. Bottom reflection loss for different sea bed materials as a function of the grazing angle are shown in Figure 8. Hard bottom materials have lower reflection loss than the soft ones. At low grazing angles, e.g. far from a surface ship, all bottom materials have low reflection loss. In homogeneous bottom sediment the reflection loss is frequency independent. In a sea bottom comprising more than one sediment layer, the reflection loss becomes more complex and frequency dependent.

The sea surface and bottom form a waveguide in shallow water. There is a cut-off frequency, below which the sound does not propagate in the waveguide in far distances, and thus can be detected only near the source. The cut-off frequency can be estimated by the formula (Au and Hastings, 2008)

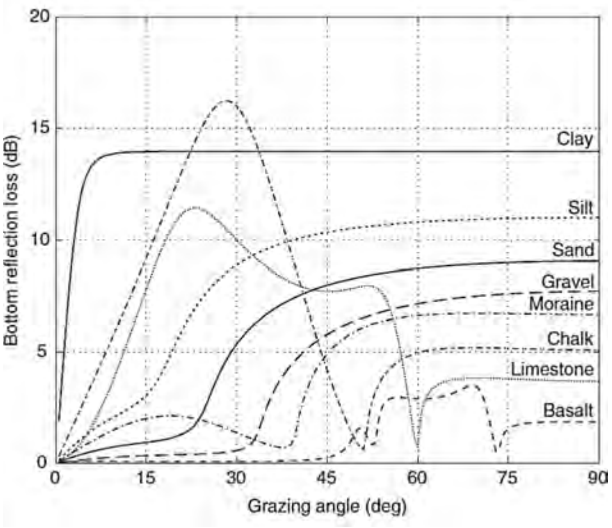


Figure 8 Bottom reflection loss vs. grazing angle for various bottom types (taken from Jensen et al., 2011)

$$f_c = \frac{c_w/4H}{\sqrt{1\text{-}c_w^2/c_b^2}} \qquad (8)$$

where c_w and c_b are the speed of sound in water and in bottom, respectively, and H is the water depth.

At higher frequencies, the sea bottom performs as a scattering surface. A simple characterisation of bottom backscattering can be written using the Lambert's rule as (Urick, 1983)

$$S_B = A + 10\log \sin^2\phi \qquad (9)$$

In an ideal case where all incident energy is scattered into water, the parameter A equals-5 dB. In real sea bottom, the parameter A has values ranging roughly from-17 dB to-35 dB having lower absolute values at hard bottoms (Makris, 1999; Rossing, 2007; Jensen, 2011). Katsnelson et al. (2012) have collected from various sources experimental figures of backscattering strengths for different bottom sediments at a frequency range from 2 kHz to 200 kHz, and with different grazing angles for frequencies from 10 kHz to 100 kHz.

As there is higher dissipation of noise at lower and higher frequencies in shallow waters, there exists an optimum propagation frequency at mid-frequencies. The optimum frequency is highly dependent on the water depth. The optimum propagation frequency has been studied e. g. in Jensen and Kuperman (1983) and Abbot et al. (2003).

6.3 Prediction Methods

Predicting propagation loss is a principal requirement for many aspects of hydrodynamic noise. Propagation models are needed in generating noise maps for target sea regions. Predicting propagation loss in sea trials in shallow waters often use propagation models that require as input well known acoustic boundary conditions.

The source level (SL) can be calculated from the background corrected measured noise level (SPL') by taking into account the propagation loss (PL) as

$$SL = SPL' + PL \qquad (10)$$

In the nearfield of a noise source the geometrical propagation loss can be approximated to be spherical

$$PL = 20\log \frac{r}{r_o} \qquad (11)$$

where r is the range and $r_0 = 1$ m is the reference distance. In the far field in shallow water the geometrical propagation loss is cylindrical

$$PL = 10\log \frac{r}{r_o} \qquad (12)$$

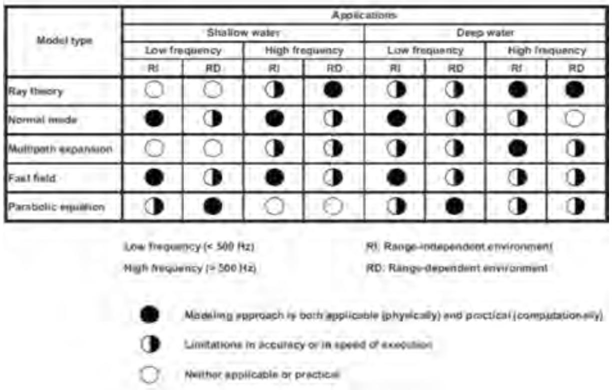
In the widely referred work of Marsh and Schuldkin (1962), the sound propagation in different conditions in shallow water was investigated. The investigation was based on about 100,000 measurements over a frequency range of 100 Hz-10 kHz. In the study, the authors defined the nearfield and far field regions based on the depth of an effective skip distance H_s, formulated based on depth of the mixed surface layer L and the water depth H as

$$H_s = \sqrt{(L + H)/3} \times \left(1000\sqrt{r_0}\right) \qquad (13)$$

where $r_0 = 1$ m. The spherical transmission loss was detected at a zone of direct ray paths at $r < H_s$. At the intermediate distances, an acoustic mode stripping phenomenon takes place. At the intermediate ranges the authors used the transmission loss of $T_l = 15\log\frac{r}{r_o}$. The mode-stripping process was found to be completed at a distance of $r = 8H_s$, after which the cylindrical transmission loss takes place. Based on this formulation, the typical distances used at ship underwater noise measurements are under spherical transmission loss range.

As highlighted in the full scale noise measurement survey of the Committee, the transmission loss over a specific region can be determined by measuring the noise levels from a calibrated noise source. The noise source is either broadband or the transmission loss can be studied at several discrete frequencies in the investigated range.

Etter (2009) and Farcas et al. (2016) have made reviews of existing propagation model types based on their practicability and accuracy. They have divided the propagation models based on several underlying mathematical methods, such as ray theory, normal modes, multipath expansion, wavenumber integration (i.e. fast field method) and parabolic equation. A detailed description of these models can be found in text books of underwater acoustics, e.g. Jensen et al. (2011) and Etter (2013). The ranking of the propagation models is shown in Figure 9.



Model type	Applications							
	Shallow water				Deep water			
	Low frequency		High frequency		Low frequency		High frequency	
	RI	RD	RI	RD	RI	RD	RI	RD
Ray theory	○	○	◑	●	◑	◑	●	●
Normal mode	●	◑	●	◑	●	◑	◑	○
Multipath expansion	○	○	◑	◑	◑	◑	●	◑
Fast field	●	◑	●	◑	●	◑	◑	◑
Parabolic equation	◑	●	○	○	◑	●	◑	◑

Low frequency (< 500 Hz)
High frequency (> 500 Hz)
RI: Range-independent environment
RD: Range-dependent environment

● Modeling approach is both applicable (physically) and practical (computationally)
◑ Limitations in accuracy or in speed of execution
○ Neither applicable or practical

Figure 9 Domains of applicability of ocean-acoustic propagation models (taken from Etter, 2009)

The models are ranked based on their capability to predict propagation in shallow or deep water and if they can predict the propagation of low or high frequency sound. Additionally, the models are divided into range independent (depth-dependent only) and range dependent models. According to Etter (2009) the range independent models can be an appropriate approximation for stable shallow water environments with locally flat bottoms. In shallow waters at low frequencies the acoustic modes interact in the bottom. The ray theory does not take into account these effects and thus cannot be applied in these cases. However, there are hybrid methods available, where the theories of several approaches have been coupled.

In the paper of Farcas et al. (2016), the authors emphasize that the propagation modeling is sensitive to the environmental data inputs that are used. In their example, the authors varied the sound speed of the sand bottom in shallow water from 1800 m/s to 1650 m/s and revealed a difference of 8-10 dB in propagation loss at a 1-5 km distance from the source.

In shallow water and at short range, the spatial variations of the sound speed are typically small and their effects on sound propagation are generally smaller than the effect of the interactions with the seabed. Seasonal temperature changes can have a substantial effect on propagation loss since the interaction at the water-seabed interface depends on the speed of sound in water (Farcas et al., 2016).

Propagation models have been used to generate noise maps at certain sea regions. Recently three EU funded research projects have generated noise maps around European waters caused by shipping, namely BIAS, AQUO, and SONIC. The former one has modeled the noise map at the Baltic Sea based on long-term measurement (about one year) of underwater noise at about 40 static locations around the sea. The project established a seasonal soundscape map by combining measured sound with advanced three-dimensional modeling (Sigray et al., 2016). The SONIC and AQUO projects concentrate more on detecting noise caused by a single or few ships in a certain region and generalizing the results to a larger region based on the shipping density.

The paper of Colin et al. (2015) shows selected results from a sound mapping workshop held in Madrid in 2014. The workshop included several test cases having single and multiple noise sources (ships) in varying environments. A number of noise propagation codes based on different theories were used in the workshop. Larger deviations in the results were observed especially at larger distances (>20km) from the sources between parabolic equation and ray based models.

Koessler et al. (2013) validated two normal mode codes against a reference solution based on a wave number integration method with one code giving good predictions while the other gave a poor prediction. The few examples above highlight the fact that the propagation loss codes must be selected based on validated results on a specific environment and frequency range.

7 FULL SCALE NOISE MEASUREMENTS

7.1 Survey

To support addressing numerous of the assigned Terms of Reference, the Committee developed questionnaires to survey the activities, approaches and opinions within the community regarding Full Scale ship underwater noise measurements. Responses to the questionnaires were solicited from ITTC members and associated principals in industry/academia.

The Full Scale ship underwater noise measurements questionnaire was sent to fifteen ITTC members and associated industry/academia involved with measurement of underwater ship noise. Nine organizations from eight countries provided responses which were very helpful in gauging the purpose, approaches and methods of measuring ship-generated underwater noise. A table of the questions and collected responses is provided as an appendix in the electronic version of the Committee Report.

The questionnaire had five primary sections covering; (1) cataloging responder information; (2) information regarding Procedures and Guidelines that are used/followed; (3) information regarding noise measurement procedures and testing conditions; (4) availability of full scale measurements for future efforts; and, (5) responders to provide any further comments.

The responses to various topics illustrate the diversity of the range of environments and ship types for which underwater noise measurements are made, the different organizations that are involved, and the objectives of measurements. Responders generally found the ITTC Full-Scale Hydrodynamic Noise Measurements Procedures and Guidelines (P & G) to be helpful. Among the various suggestions for possible P & G improvements were to expand on shallow water measurement issues and provide guidance on the most appropriate standard to use for a particular measurement case.

Four Standards/Guidelines were listed as being at least partially followed of which three were also listed as being preferred. Nearly all responders think Procedures and Guidelines for shallow-water measurements are feasible and would be helpful. Similarly nearly all responders think ‘Source Level’ is a reliable quantity to quantify underwater noise emission levels and be used for comparing different designs and for assessing environmental impact. Several responders noted potential sources of uncertainty that are problematic in determining

Source Levels from measured Sound Pressure Levels.

The range and diversity in questionnaire responses is in part due to the various purposes of testing (ship type) and testing objectives. Figure 10 show the responses to questions 3.1 regarding the purpose of testing and Figure 11 shows the responses to question 3.2 asking the goals/objectives of the testing. No responders stated that Full Scale testing was supported/guided by Model Scale testing. The most common Full Scale performance predictions made prior to testing were based on analytical/numerical studies.

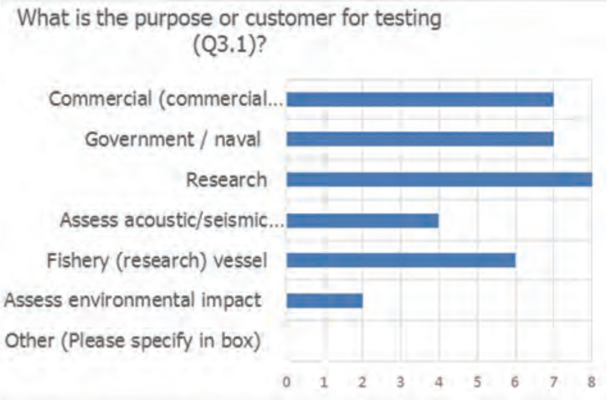


Figure 10 (Q3.1) What is the purpose or customer of testing? Number of responder on horizontal axis

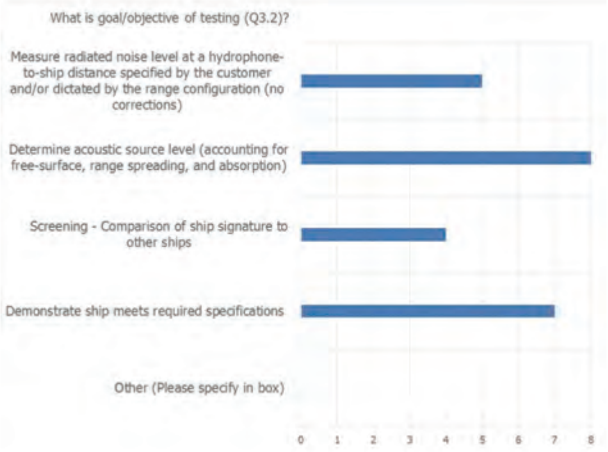


Figure 11 (Q3.2) What is the goal/objective of testing? Number of responder on horizontal axis

A range of responses was given for questions related to vessel testing parameters. A majority of responders replied that testing was done over multiple conditions. The reasons for multiple conditions are shown in Figure 12 (Q3.15).

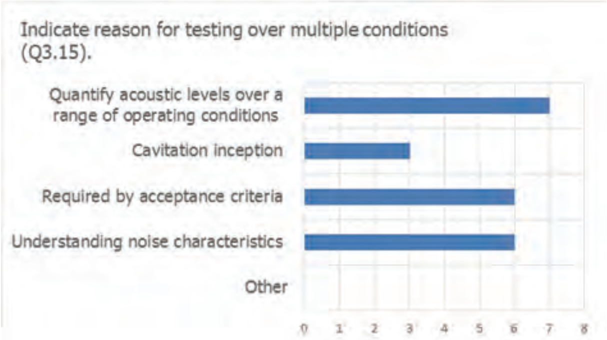


Figure 12 (Q3.15) Indicate reason for testing over multiple conditions. Number of responder on horizontal axis

Most responded that the maximum sea-state for which measurements are made is sea-state 2 or 3 (Beaufort 2 or 3); five stating that restriction was due to acoustic levels; three replied it was due to hydrodynamic issues; and, two replied it was a limit based on deployment of the mobile array system and/or concern for the acquisition system and safety.

For the topic of acoustic testing responders stated that measurements were made in shallow water (six) and deep water (seven). The range and variation of responses to questions in this category illustrate the wide range of conditions and environments for, and in which, underwater noise measurements are made.

Questions related to measurements and data issues were posed to elicit information on how measurement uncertainty was assessed and handled. Only three responded that multiple runs were performed (two to four). Regarding categories of uncertainty; four responses stated they do not categorize uncertainty; one response each to operational conditions and acoustic source as being categories; and, two each to environmental and instrumentation as being categories. About half of the responses indicated that uncertainty was handled by following one of the published standards/guidelines.

There were not many responses to questions regarding requests for full scale and/or model scale measurements that could be shared by the ITTC community and the responses received are discussed elsewhere in this report.

7.2 Noise Measurement Procedures and ITTC Guidelines

This section includes a brief summary of material provided in the ITTC Underwater Noise from Ships, Full Scale Measurements P&G (7.5-04-0-01, Rev. 1, 2017). That document should be referred to if further details are needed.

The procedures and methods for full scale noise measurements are dictated by the objectives and purpose of the measurements program. The ANSI and ISO standards, which are in part a basis for the ITTC Ship Underwater Noise Full Scale Noise Measurement guidelines, provide measurement standards for three grades of measurement quality; (1) precision grade, (2) engineering grade, or (3) survey grade. The AQUO WP-3 document (Moreno 2014) recommends procedures for two grades of measurements; (A) for engineering purposes with high accuracy and repeatability, and (B) for comparison to noise limits with medium accuracy and repeatability. Those procedures address both shallow water (A1/B1) and deep water (A2/B2) measurements.

Results from the Full Scale questionnaire showed that there is a broad range of customers for full scale underwater noise testing and the objective of the testing ranges from screening (comparison of a ship's noise levels to other ship) to determination of acoustic source levels.

Measurement type. The basic underwater noise measurement is that of Sound Pressure Level (SPL), which is the acoustic pressure measured at a hydrophone location expressed in decibels (the P&G provides further information). As interest is in the frequency content of the pressure, the acoustic pressure in the SPL is often a narrowband level (for example in equivalent 1 Hz bandwidths) or a level in a proportional band (for example 1/3-octave).

Recognizing that in situ measurements of ship noise may include unwanted contributions from background noise (e.g. sea state noise), SPL measured during an acoustic trial are periodically compared to measurements of background noise and when appropriate and warranted, background noise corrected SPL (SPL') are calculated by power subtracting background levels from the measured SPL.

Since acoustic waves geometrically spread in radiating from the ship to the location where measurements are made, underwater noise measurements are often expressed as radiated noise levels (RNL) which is the measured SPL (or SPL') measured at distance ‘r’ from the ship adjusted to an equivalent level at a range of 1 m, assuming spherical spreading, by adding 20 $\log_{10}$(r/1 m) to the SPL levels.

For purposes of noise screening, determining SPL' or RNL may be sufficient. However, to determine source level (SL) a detailed estimate of the propagation loss (PL) between where the ship noise is generated and where it is measured is needed. Prescribing a ship's acoustic SL is effectively specifying the equivalent level a monopole source would generate in an unbounded ocean at a distance of 1 m from the source. Effects contributing to PL include, in part, geometrical spreading, absorption, transmission path refraction due to sound speed variations, and contributions from surface and bottom reflections. The overall uncertainty in estimating SPL', RNL or SL depends on how well the ship-to-hydrophone geometry is known and how well PL can be determined. Methods to understand and minimize uncertainty in reported underwater noise levels is to use multiple hydrophones, as in a vertical line of hydrophones spaced at various distances from the free surface, and to acquire measurements for multiple and various runs past the hydrophones.

Measurement Configuration. Underwater noise measurements are made using a single hydrophone or multiple hydrophones comprising an array or string. The basic configuration for deploying hydrophone(s) for underwater noise measurements is surface mounting where hydrophones(s) are suspended from a surface buoy or support platform, or using a bottom anchor and subsurface riser buoy combination onto which the hydrophone(s) are attached.

Due to the significant impact the air-water interface (sea surface) has on propagation characteristics of underwater ship noise, accurately knowing the position of measurement hydrophone(s) relative to the sea surface is important. The deployment arrangement for hydrophones recommended in the ANSI and ISO standards depends on the grade of measurement needed. For the two higher grades (precision grade and engineering grade) it is recommended that a vertical string of three hydrophones be deployed at depths such that when the test ship is at the Closest Point of Approach (CPA), the ship-to-hydrophones configuration be such that the hydrophones are at angles of 15°, 30° and 45°, to the ship as measured from the sea surface (Figure 13).

Measurements from a single hydrophone positioned at the 45° depth can be used for the lowest grade measurements. For the higher grades, measurements from the individual three hydrophones are power summed to reduce the influence of sea surface reflections (Lloyd mirror).

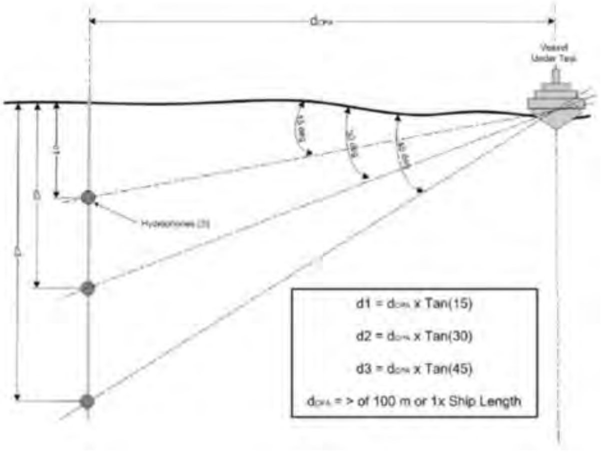


Figure 13 Hydrophone geometry; ISO Grade A and B

The testing sequence for measurements of underwater noise entails the test ship sailing a straight course past a sea surface reference point that is indexed to the location where the measurement hydrophone(s) are deployed. During the passage, the ship maintains a specified speed and equipment line-up. Hydrophone(s) data are continuously obtained during the period of vessel passage. The track of the vessel is such that it passes the array with a CPA that is selected to meet specific test requirements.

Recommendations from the AQUO project, adopted in the BV rule, specifies an expanded series of such runs past the array to acquire data at multiple CPA to aid in accounting for propagation losses (Figure 14). Six runs are recommended. Test runs are made for both port and starboard aspect at three different CPA; i) 200 m or distance of 1 ship length, ii) 400 m or distance of 1.5 ship length, iii) 500 m or distance of 2 ship length. Results from these varying CPA aid in assessing source-to-receiver propagation characteristics. Recognition is given of possible issues with low signal-to-noise for quieter ships at the greater CPA. Repeat runs at the closer CPA are recommended to help determine repeatability. Accuracy of CPA distance is specified to be +/-10 m.

Knowing ship-to-hydrophone geometry

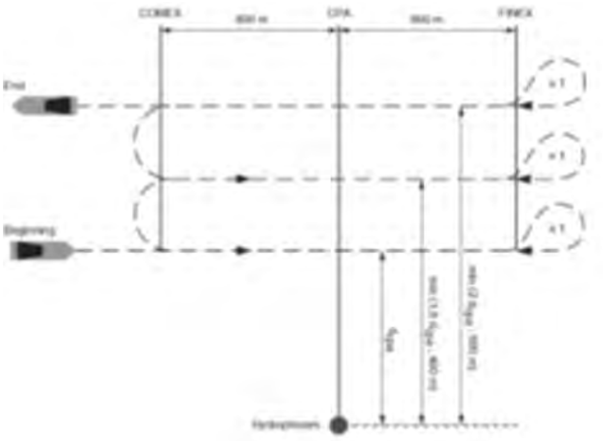


Figure 14 AQUO/BV rule multi-CPA test configuration for grade B applications

during testing is critical in converting SPL to either RNL or SL. Ship position can be tracked with sufficient accuracy using GPS or preferably DGPS. Consideration of actual hydrophone position must be given if sub-surface conditions/currents are such that hydrophones are not directly below the index position.

As discussed later, ship underwater noise may vary with ship aspect. Here ship aspect refers to the azimuthal direction relative to the ship with bow, beam, and stern being cardinal aspects. Often only beam aspect is measured. Beam aspect levels may be defined as the average noise levels measured over the ship track covering ± 30° of CPA. However, various groups use other angles of track to represent beam aspect. When high accuracy estimates are needed, continuous noise measurements are sub-divided into short time intervals (typically 1 second), individually corrected for propagation effects, and then power averaged over the beam aspect sector to arrive at the estimate for beam levels. Lower grade estimates can be made based on a time average of levels covering the full period over which the ship is sailing the beam sector.

It is generally recommended that for each operating condition of interest, a minimum of two sets of measurements be acquired for both port and starboard aspect to allow for averaging and determination of possible port-starboard asymmetry. For high grade measurements, as defined in the ANSI/ISO standards, it is recommended that three runs for each aspect and condition be obtained.

For reporting purposes, port and starboard aspect measurements can be compared for difference in level. If levels measured for the two sides are within (nominally) 3 dB of each other, the two levels can be averaged and reported as a single level. If levels are different by more than that amount, port and starboard levels are generally reported separately.

During passage of the test ship past the hydrophone(s), operating conditions should be kept as constant as possible. Such operating conditions include ship speed, shaft RPM, propeller pitch (for controllable pitch propellers), ship power, rudder angle, and on-board equipment. Specifying the variation in these operating conditions that is acceptable is not possible due to dependence on ship size and ship type. However, acceptable variations in ship speed are generally reported to be ±0.3 kn or within ±2% of the target speed. Note that the proper ship speed for hydrodynamic noise is speed through water (STW) versus speed over ground (SOG as provided by GPS). Acceptable variations in propeller shaft RPM are generally ±2.4% of the target RPM. For controllable pitch propellers, propeller pitch angles should not change during the noise measurements. A general guideline is to not operate the rudder or keep variations to within ±2.0 degrees .

If underwater noise measurements are conducted as part of contractually required speed-power trials then ITTC Recommended Procedures and Guidelines for Speed Power (S/P) Trials (7.5-04-01-01.1, 2014) should be followed. Those recommendations and guidelines are generally worthy of review and adopted as general testing protocol.

Testing Configurations. The manner and

procedures followed for measuring underwater noise can vary due to site-specific requirements/restrictions, test objectives, and customer requirements.

For commercial ships, sea trials including speed power (S/P) and manoeuvring trials are carried out at various main engine loads before delivery of the ships. Many times the effect of the noise measurements on the cost and duration of sea trials is limited by conducting the noise measurements during the conventional sea trial program. It is recommended that if measurements of underwater noise are to be performed during S/P trials, runs at Contract and EEDI (Energy Efficiency Design Index, as formulated by IMO) power conditions be performed. It has been recommended that during speed power trials, at least four double runs for the first delivered ship and three double runs for sister ships including EEDI power be performed (ITTC 7.5-04-01-01.1, 2014). Manoeuvring trials are not mandatory for sister ships.

In the case of a series of ships of the same type, measurement results of the first vessel are often used to represent noise performance of the other vessels. However, there are potential concerns with this approach due to ship-to-ship variability. While a subject of study, differences in sea trial results between sister ships may be attributed to variations within the manufacturing tolerance of a ship and environmental conditions existing during noise measurements. It is noted that the manufacturing tolerance of ships described in IACS REC 47 Rev.7 (2013) is ± 0.1% of LBP, breadth and depth of ships. The manufacturing tolerance of propellers described in ISO 484-1 is ± 0.3% for diameter and ± 0.75% for mean pitch values in case of Class I.

Environmental Conditions. Environmental conditions during underwater noise measurements can significantly influence the quality of results. Issues related to water quality/characteristics can influence range correction estimations; sea state, wind speed and direction can have an influence on ship hydrodynamic performance, and hence acoustic performance; and, ambient underwater noise, which sets a noise floor for ship underwater noise measurements, is a function of wind speed and wave height. As illustration, the variability of environment conditions that existed during standard speed trials for seven container ships was reviewed by Lee (2015). It was found that the range of wind speeds, wave heights and water temperatures were, 3.0 – 10.4 m/s, 0.4 – 1.7 m and 12.0 – 23.0℃, respectively. Since background noise is the most important environmental parameter it needs to be monitored and recorded during the conduct of all underwater noise measurements. When necessary, background noise needs to be power subtracted from measured SPL providing noise-free SPL'.

The ITTC P & G for Speed and Power Trials provides a listing of boundary conditions (location, wind, sea state, water depth, and current) that should not be exceeded in order to arrive at reliable speed/powering results. However, as discussed, more restrictive limits to wind, sea state and current may need to be imposed to ensure reliability of underwater noise measurements.

Depending on location and situation water current at the surface (affecting STW vs. SOG) and at the hydrophone(s) location can be important and needs to be measured. Due to the importance of accurately estimating PL, water temperature, density, and sound speed as a function of depth need to be monitored and recorded during the conduct of testing.

Ship Configuration. Considering the potential important of propeller and hull conditions to ship underwater noise, a maintenance inspection should be made of the conditions of the propellers and hull as close in time to the testing period as possible. Particular attention should be given to the conditions of the propeller(s) and possibility of excessive marine growth. Propeller fouling not only possibly reduces ship/speed relationship but can result in earlier cavitation onset and overall higher propeller noise levels. The pre-trial Ship Condition monitoring recommended in the ITTC Procedures 7.5-04-01-01.1 provides an excellent set of guidelines to follow for this purpose.

Directivity. Ship noise has a directivity with respect to depth (depression angle) and azimuth as shown by Arvesson & Vendittis (2000) for a single screw bulk cargo vessel, length 173 m. The variability with respect to depth is caused by the Lloyd-Mirror effect that is discussed in Section 6.2. The radiation of cavitation noise is influenced by the shielding effect of the hull in front of the propeller and the bubbly wake aft of the propeller. At 350 Hz, the cavitation noise level in bow and stern aspect at 20 deg depression angle is smaller by approx. 11 dB and 8 dB, respectively, compared to beam aspect. At the blade rate frequency the variation with azimuth angle is small (approximately 2 dB). Near bow aspect the levels change gradually while near stern aspect the levels change more rapidly. The directivity with azimuth is also presented by Trevorrow et al. (2008) for a single screw oceanographic vessel, length 40 m, in the frequency range between 160 Hz and 4 kHz. The propeller was cavitating for the ship speed considered. The variation does not depend on frequency and the influence of the depression angle, that varies with azimuth, is thus considered negligible. The variation with azimuth angle θ, defined with respect to bow, was found to be well described by

$$\Delta L_p = 10\log_{10}[\cos^{1.95}(\theta-\theta_0)+0.08] \quad (14)$$

where $\theta_0 = 97\text{deg.}$ is the peak direction. The variability is presented in Figure 15. Bow and stern aspect have 10 dB lower values than beam aspect where the variation near the bow is more gradual than near stern.

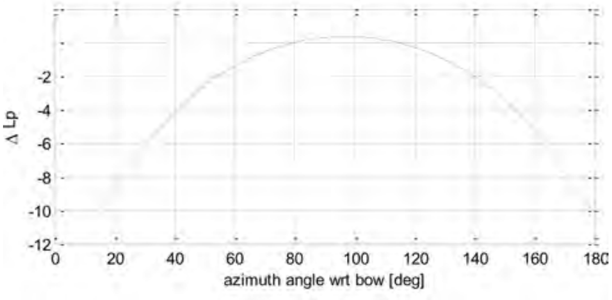


Figure 15 Directionality pattern as presented by Trevorrow et al. (2008)

Gaggero et al. (2013) present the directivity with azimuth angle for three ships, a single screw fishing vessel, length 26 m, a single screw fishery research vessel, length 67 m and a twin screw merchant vessel, length 209 m. The directivity pattern was very similar for the four frequency bands that were investigated between 63 Hz and 5 kHz, although the variation in levels between bow, stern and beam aspect showed some differences. The directivity for the research vessel is similar to the results by Arvesson & Vendittis, and Trevorrow et al., although the variation in noise levels with azimuth angle is somewhat larger. Bow and stern aspect were not measured in detail for the merchant vessel. The small fishing vessel shows a completely different directivity pattern with maximum noise levels at 150 and 180 deg. (stern aspect) which can be 20 dB higher than beam aspect. The variability in low frequency noise bands (40, 95 and 800 Hz) for three ship types is also presented by McKenna et al. (2011) with the difference that minimum distance between receiver and ships is 3 km. The values when the ship was advancing (bow to beam aspect) were for most cases lower than when it was receding (beam to stern aspect) which is consistent with the results discussed above although the reported variability is much higher: differences are typically between 5 and 10 dB over a small range of azimuth angles with respect to beam aspect.

7.3 Shallow Water

Water depth at a test site is an important issue that affects the quality of measurements that can be obtained and the type of deployment system that is used. While preference is naturally for deep water tests, for which the influence of bottom reflections on acoustic propagation are not significant, the off-shore waters of many countries consist on an extended continental shelf which is characteristically shallow water (Yezhen and Wenwei, 2015). Further, the infrastructure needed to support measurements in deep water is more complicated and periods of low background noise (low sea state conditions) are less often.

In shallow water the noise characteristics of the ship and the geo-acoustic characteristics of the ocean bottom are important. To minimize bottom effects the ANSI and ISO standards recommend for the highest grade measurements that tests be conducted with a minimum water depth of 300 m or three times ship length, 150 m or 1.5 times ship length for middle grade measurements, and 75 m or 1 times ship length for the lowest grade measurements. These recommendations are set in part to ensure measurements include acoustic contributions that may exist along the full length of the ship, bow-to-stern.

If the dominant contributor to underwater noise is the propeller (via propeller cavitation) then the ship-length criterion may be relaxed. Similarly, if underwater ship noise is due to only machinery and propeller noise contributions, then the ship length criterion may be reduced to being the distance between the machinery room and propeller, rather than being overall ship length. Consideration needs to be given to whether ship operational performance is impacted while operating in shallow water which could affect acoustic performance. Information on the influence of shallow water on speed and power trials is given in ITTC procedure 7.5-04-01-01.2.

The AQUO D3.1 and BV documents provide very extensive reviews of the effects of acoustic signal transmission and bottom absorption/reflection in measurements of underwater noise. It is noted that an ISO procedure on noise measurements in shallow water is in development.

It is to be noted that the classification societies use the geometrical propagation loss close to the spherical one. DNV silent class notations (2010) estimates propagation loss $PL \sim 18\log\frac{r}{r_o}$, and Bureau Veritas URN Rule Notes (2014) $PL \sim 19\log\frac{r}{r_o}$ in water depths < 100 m, and $PL \sim 20\log\frac{r}{r_o}$ in water depths > 100 m.

In shallow water of coastal regions and on the continental shelves, the surface and seabed act as boundaries which "channel" the sound between them with the action of a waveguide, see Section 6. Also the velocity profile tends to be irregular and unpredictable, and is greatly influenced by surface heating and cooling, salinity changes, and water currents (Urick, 1983).

In shallow water, multipath transmission occurs even at short ranges. Mackenzie (1962) observed variations of as much as 50 dB in the intensity of a continuous wave tone transmitted over a range of a few kilometers. He identified and described the fluctuation-producing mechanisms as due to: (1) seasonal effects, such as temperature gradient producing better transmission during winter; (2) storms; (3) tidal changes, such as the effect of tidal flow on the phase delay between source and receiver; (4) fish, producing better transmission by day than night; and (5) surface waves.

Estimation of source level from sound pressure measurements in shallow reverberant channels is not easy since an estimate must be made of the true propagation loss, which is complicated by the interactions of sound with the sea bed and sea surface. This could be done with a sound propagation model which has accurate input data for all parameters (including the environmental parameters), but in practice this is often estimated empirically (Robinson et al., 2014).

In order to empirically determine the propagation loss for deriving the source level from measured ship SPL, measurements may be made as a function of range from the source (Nedwell et al. 2007, De Jong et al., 2008, Robinson et al., 2013). This is particularly beneficial for measurements in shallow water where it would be difficult to predict accurately the propagation loss with a purely theoretical model.

Figure 16 shows a potential deployment configuration for measuring radiated noise in shallow water with static recorders or hydrophones deployed from a vessel which is anchored (Robinson et al., 2014).

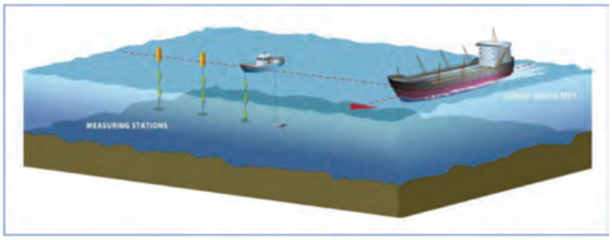


Figure 16 Deployment configuration in shallow water (taken from Robinson et al., 2014)

If using two hydrophones in shallow coastal water, it is recommended that these be placed at two depths in the lower half of the water column, ideally between 1/2 and 3/4 of the total depth with the separation between hydrophones maximized (de Jong et al. 2011).

Anton et al. (2012) evaluated differences in reported underwater acoustical radiated noise levels of ships under various boundary conditions. A relevant amount of measured data shows good agreement between the measured under water noise radiation of various noise sources and ships under different machinery configurations, although the propagation conditions between the two ranges differ considerably. Even at frequencies below 100 Hz, the differences are less than expected.

Third-octave acoustic Radiated Noise Levels are presented in Figure 17 for 10 merchant ships measured while entering or exiting shipping ports. Investigations show that there is little or no source level dependence on ship speed or displacement for the ships measured (Hallett, 2004).

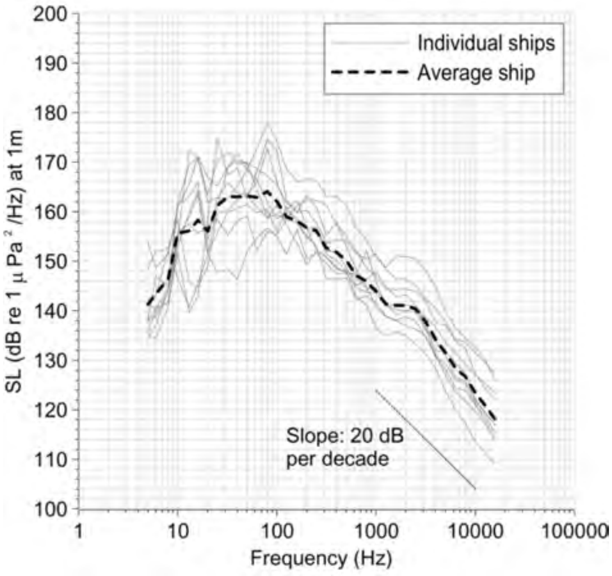


Figure 17 Individual merchant ship Radiated Noise Levels, plus average (taken from Hallet, 2004)

Hahn et al. (2010) show the interference structure of the received signal in the frequency domain for both rock and sand bottom in shallow water. The pressure level of the rock bottom is generally higher than the sand bottom. This is because sound pressure is more attenuated in the sand bottom than the rock bottom.

The ambient noise levels in shallow water are subject to wide variations. In such locations, the sources of shallow water noise are highly variable, both from time to time and from place to place. At a given frequency in shallow water the noise background is a mixture of three different types of noise: (1) shipping and industrial noise, (2) wind noise and (3) biological noise (Urick, 1983).

Increases in noise level with wind speed have been found to be 7.2 dB per wind speed doubling, or an increase of intensity slightly greater than the square of the wind speed. The measured levels are nominally independent of depth, water depth and other site characteristics. At low frequencies and at the low wind speeds, shallow water can be appreciably quieter than deep water. In bays and harbors, the noise of industrial activity of human origin, the noise produced by marine life, and the turbulence of tidal currents, all add to create a noisy ambient environment (Urick, 1983).

The Bureau Veritas URN rule notifications (2014) suggest as the first option to calculate the transmission loss at the noise trials at low frequencies (< 1000 Hz) using a range independent wave integration model (Scooter/Fields), and at high frequencies (>1000 Hz) a range dependent ray trace based model (Bounce or Bellhop). Other methods and codes can be accepted if the validation references are available. There are other open source propagation models available, e.g. U.S. Office of Naval Research in http://oalib.hlsresearch.com/.

7.4 Uncertainties and Variability

Measurement of ship underwater noise is subject to potentially large variations that need to be controlled and understood in order for the measurements to be of use. Numerous studies have been made to understand and quantify the source and impacts of these variations, particularly in support of drafting of the various standards, classifications, and guidelines. Attention is given to four publications that address these issues. It is noted that while the terms variability, repeatability, and error are potentially used somewhat interchangeably, they can mean different aspects of results in a final level of uncertainty. It is further noted, but not expanded upon, that in uncertainty analysis a distinction is made between Type A uncertainty, which is uncertainty evaluated by statistical analysis of a series of observations and Type B uncertainty which is evaluated by non-statistical methods.

Sponagle (1988) provides a fairly thorough evaluation of variability of ship noise measurements viewed from a statistical/regression analysis perspective. Issues considered included; errors in spectral analysis, Doppler shift, multi-path transmission, attenuation, measurement time, changes in signature levels due to changes in ship resistance, and environmental factors. The regression analysis, applied to a large number of sea trial data involving cavitating propellers, gave an average uncertainty estimate, at 95% confidence level, of 4.8 dB for a single dataset and 6.5 dB for combined data sets. A single data set consists of noise spectra measured within a period of a few days and combined datasets consists of noise spectra for the same ship measured at different times over a period of several years.

Gaggero, et al. (2012) addressed uncer-tain-ties in the measurement of, and effects on marine environment of, ship underwater noise emissions. The approach for assessing measurement uncertainty was to consider variations that can exist while following the allowable confines of various standards and determining the uncertainty that results. Issues considered were: (1) hydrophone position, as influenced by motions of the ship from which the array is deployed and ‘kiting’ of the array, and (2) variations in the sound transmission path (propagation loss) as a function frequency, source/receiver positions, water celerity profile, bottom composition and water depth. The general findings were that hydrophone position errors were less at greater CPA and that using simplified laws, large differences between measured and prediction losses are observed at low frequency while reasonable comparisons are found at higher frequencies.

Undertaken as part of the SONIC project, Humphrey, et al. (2015) reviewed the variability of underwater ship noise measured with two hydrophone arrays from a small vessel in shallow water. Comparison of data from the two arrays demonstrated typical variability and repeatability of underwater ship noise measurements using mobile arrays. The standard deviation (70% uncertainty) of levels from a single hydrophone for several runs is between 1 and 2 dB, but it may increase significantly at low frequency for hydrophones deployed relatively close to the free surface. Systematic differences between hydrophones deployed at different depths were observed for frequencies below 1 kHz while for higher frequencies differences between hydrophones were of the same order as the variability for a single hydrophone.

The AQUO WP-3 document (Moreno, 2014) provides not only an extensive review of existing standards and procedures, and proposes a new under-water noise measurement procedure. Included are estimates of both uncertainty and repeatability that are expected to be achieved if the procedures are followed. Procedures are proposed for two grades of measurement for both shallow water and deep water conditions. Grade ‘A’ is for engineering purposes, with high accuracy and repeatability, and Grade ‘B’ is for comparison to noise limits with medium accuracy and repeatability. Grade A1 and B1 apply to shallow water measurements and A2 and B2 to deep water. Five measurements-related categories for uncertainty and repeatability were considered: (1) Distance Measurement Accuracy, (2) Noise recording accuracy, (3) Propagation/Transmission loss, (4) Vessel, and (5) Post processing. The Vessel category covers issues of speed, propeller/machinery conditions, load conditions, and currents. A theoretical study of expected uncertainty for each category was made. The values for repeatability are identical as for the uncertainty but exclude contributions from noise recording and transmission. Table 5 is a modified copy of the uncertainty and repeatability estimates provided in the AQUO document. In the original tables a distinction is made between deep and shallow water, but apart from the grade A U(D) term the numbers for the uncertainties are identical so they are not listed separately in the Table. These theoretical estimates were found to be in general agreement to estimates based on review of a set of ship noise data.

Table 5 Computed estimates of the uncertainty U and repeatability R at 95% confidence level for the URN measurements procedure of the AQUO project (Moreno, 2014)

Grade		A①	B②
Accuracy type		engineering	comparison
Distance accuracy measurement	U(D), R(D)	1 dB	1.5 dB
Noise recording accuracy②	U(H)	2.5 dB	4.3 dB
Transmission/Propagation loss③	U(TL)	3 dB	7 dB
Vessel	U(V), R(V)	1 dB	1.2 dB
Post Processing	U(PP), R(PP)	2 dB	2 dB
Total Uncertainty		4 dB	7 dB
Total Repeatability		1.2/2.3 dB	2/3 dB

①: In the original table a distinction is made between deep and shallow water, but apart from the U(D) for grade A, the numbers for the uncertainties are identical and are not listed separately in this table

②: Note: Due to fact that this uncertainty is only important for high frequencies, it is not accounted for in the final uncertainty of the measurement

③: Note: According to ISO 18405 the term ‘transmission loss’ corresponds to a reduction in specified noise level between two specified points whereas ‘propagation loss’ corresponds to the difference between source level and mean-square sound pressure level.

It is noted that repeatability issues may occur for ship underwater noise measurements due to unrealized changes in ship operations (equipment line-up, speed, etc.) or due to variations resulting from changes in seaway conditions (currents, wave action, etc.). Uncertainty due to ship operations can be minimized by careful attention to ship conditions and indoctrination of ship's crew as to the impact of ship operations on underwater noise. There is little control over uncertainty resulting from seaway conditions other than conducting tests only during favourable weather conditions, which is generally not possible. Seaway-related uncertainty can be minimized by assessing results from multiple runs for each condition. Repeat tests are a principal method listed by all standards and best practices as a means to mitigate/ quantify uncertainty.

Influence of operational conditions. Very little information is available on the influence of operational conditions on radiated noise levels. Trevorrow et al. (2008) made measurements of underwater noise from an oceanographic research vessel for conditions when the vessel was conducting turning manoeuvres. From these carefully conducted tests they showed that even for relatively small turning rates, underwater noise levels increased. The influence of rudder angle and heading for sea state 5 on cavitation inception has been investigated during sea trials by Verkuyl & van Terwisga (2000) and their results are presented in Figure 18. No information is given on the current.

8 MODEL SCALE NOISE MEAUSUREMENTS

8.1 Survey

To support addressing numerous of the assigned Terms of Reference, the Committee developed questionnaires to survey the activities, approaches and opinions within the community regarding Model Scale ship noise measurements. Responses to the questionnaires were solicited from ITTC members.

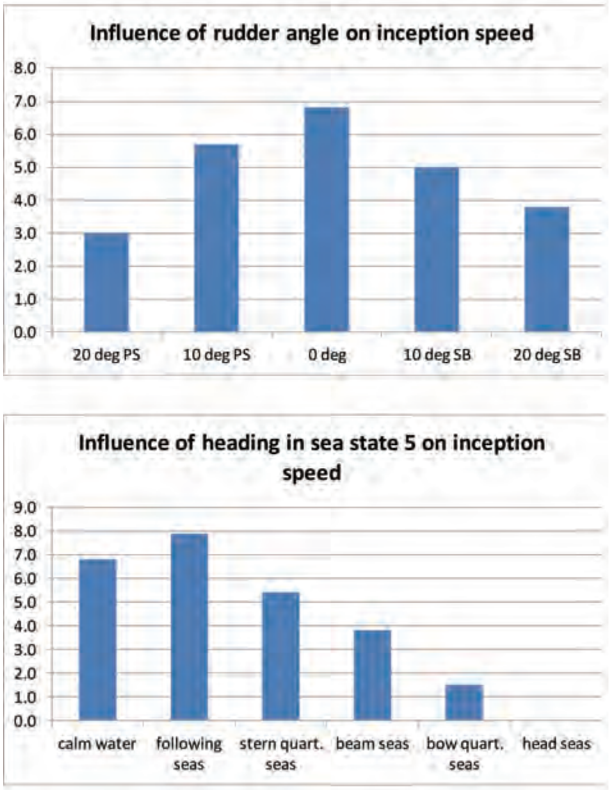


Figure 18 Influence of rudder angle and heading on cavitation inception, adopted from Verkuyl & van Terwisga (2000)

Among the 13 organizations that respond to the questionnaire, there is a strong support for the guidelines released by the 27th Noise committee along with demands for updating some of the items like reverberation, data analysis, exponent for the scaling methods, noise absorption by nuclei, feedback from comparison between model scale and full scale measurements. Main interest of the organizations that are performing model test for predicting propeller noise signature is related to either commercial or government or research requests.

Among all the organizations, the operating conditions set for the model scale testing are in line with the recommended conditions as described within the ITTC Cavitation procedure. The propeller diameter is in between 200mm and 280mm. The flow speed is set from the Froude similarity for model test in depressurized tank and the flow speed in cavitation tunnel is set at the maximum achievable flow speed related to the shaft motorization and dynamometer capacity (max torque and RPM) and related to the flow pressurization of the test section. The propeller loading is set according to the thrust / torque identity i.e. K_T or K_Q similarity. Air content settings are very broad, from 30% up to 70%.

The frequency band generally taken for the model scale measurements is with a minimum frequency set in between 0.1-1 Hz, and with a maximum frequency set in between 20-100 kHz. A majority of organizations are supporting a procedure that takes into account reverberation effects.

The organizations are also carrying out multiple operating conditions in order not only to identify the inception of cavitation but also to make a sensitivity survey of the operating conditions on the measured radiated noise.

The measurements uncertainty is generally estimated through repeated tests (on average 3 repeat tests per operating conditions). A large majority of organizations is considering that the largest uncertainty might be obtained for operating conditions close to the cavitation inception. The reverberation effect is also recognized as one possible major contributor to the uncertainty.

Finally, there is a large support for participating to a round robin test on a ship propeller on which relevant data at full scale are available.

8.2 Prediction of Cavitation Source Strength

The prediction of Cavitation Source Strength is predominantly done through scaling the measurement of the cavitation sound pressure level of a model scale propeller tested in cavitation facilities (either cavitation tunnel or vacuum tank). The present committee is recommending the use of the guideline No. 7.5-02-01-05, which have been updated by the present committee. A summary of the updates that were driven by the results of the questionnaire sent to the organizations of the ITTC community described in the appendix of the electronic version of this document, are briefly described hereafter.

The main philosophy of the model scale propeller cavitation noise measurement is similar to the one in the first version of the guidelines. The procedure to predict the source level of the cavitating propeller at full scale from the model scale Sound Pressure Level measurement is described in the guideline and summarized in Figure 19.

Four major updates have been proposed for the guideline.

First, although it might be seen as an academic recommendation, we feel important to recall the definition of the spectral representation computed from an FFT, resulting in for instance the Power Spectral Density function $\phi_{pp}(f,\Delta f)$.

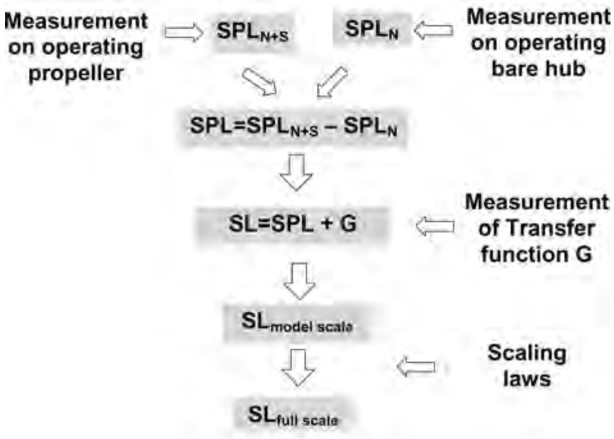


Figure 19 Procedure to obtain the cavitating propeller source level from model test measurement

The spectral representation of a sound pressure signal p(t) is either:

- the Power Spectral Density function for a constant bandwidth (very often $Df = 1$Hz at model scale). The unit of SPL is then dB re 1 μPa^2/Hz.

$$SPL(f,\Delta f) = 10 \cdot \log_{10}\left(\frac{\varphi_{pp}(f,\Delta f)}{p_{ref}^2}\right) \qquad (15)$$

- or the Power Spectrum for a constant or proportional bandwidth (1/3 octave band level). The unit of SPL is then dB re 1 μPa^2. The relation between power spectrum and power spectral density is given by

$$SPL_{\Delta f}(f,\Delta f) = 10 \cdot \log_{10}\left(\frac{\phi_{pp}(f,\Delta f)}{p_{ref}^2}\right) + 10 \cdot \log_{10}(\Delta f) \qquad (16)$$

So it is required to state clearly what type of SPL representation is used when reporting on propeller noise measurements, for instance by giving the bandwidth Δf in the subscript. The power spectrum in 1/3 octave band level can be given as $\mathrm{SPL}_{1/3}$ [dB re 1 μPa^2]. This is important when scaling the model scale SPL to the full scale SPL.

Reverberation. A second point which has been emphasized when updating the guidelines is dealing with the reverberation issues. In model scale test facilities, especially in cavitation tunnels, the sound propagation is not acting like in a free-field environment. Reverberation issues in sound propagation is referring to the effect of the sound reflecting to the hard surfaces of walls, floor and roof of the test section, in which the sound measurements are performed. It is obvious that in cavitation tunnel at least, these reflections do exist. The results of the model scale measurement questionnaire show that 9 institutes among 13 are applying corrections on acoustics measurements for wall reflection. The method generally developed is based on the use of a transfer function. An acoustic calibration is performed using a known sound source put at the propeller location in the test section. A transfer function between source and the received acoustic signal of the measurement system is then obtained, provided that the coherence between the received signal and the source signal is close to one. The calibration has also to take into account the fact that the propeller source is not exactly a monopole sound source and is also a moving source.

In a cavitation tunnel where the test section is mainly reverberant, it is recommended to take this transfer function into account as presented by Briançon et al. (2013) and Tani et al. (2015). This is done at zero flow speed and using a noise source at different locations in the propeller disk to average out the presence of standing waves. The transfer function is an average of the transfer function measured for the different locations, preferably at positions where the largest cavitation extension is expected to occur. In the transfer function measurements, the linearity of the response needs to be checked.

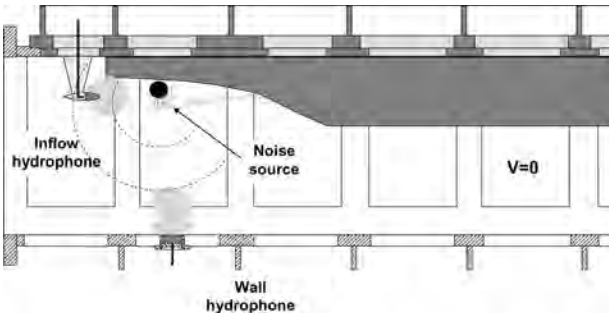


Figure 20 Transfer function measurement set-up in cavitation tunnel

If a transfer function is available, the distance normalisation of the propeller noise measurements is not required for it is taken into account in the transfer function. The transfer function G is then computed for each hydrophone using the Sound Pressure Levels of the signal of the noise source and of the signal of the hydrophone receiver:

$$G = SPL_{Source} - SPL_{Hydrophone} \qquad (17)$$

In free-field conditions, the transfer function would correspond to the spherical spreading loss using be distance r between propeller and hydrophone with $r_{ref} = 1\text{m}$:

$$G = 20 \cdot \log_{10}\left(\frac{r}{r_{ref}}\right) \tag{18}$$

The transfer function is used to compute the propeller source strength levels SL from the measured (and background noise corrected) SPL in the cavitation noise measurements:

$$SL = SPL + G \tag{19}$$

A last remark is that the noise sources available are generally calibrated for frequencies above 1 kHz. The calibration should be extended to lower range to be able to compute the transfer function for frequencies lower than 1 kHz. An example of a transfer function is presented in Figure 21. Hynninen et al. (2017) present a computational study on the transfer function in a cavitation tunnel.

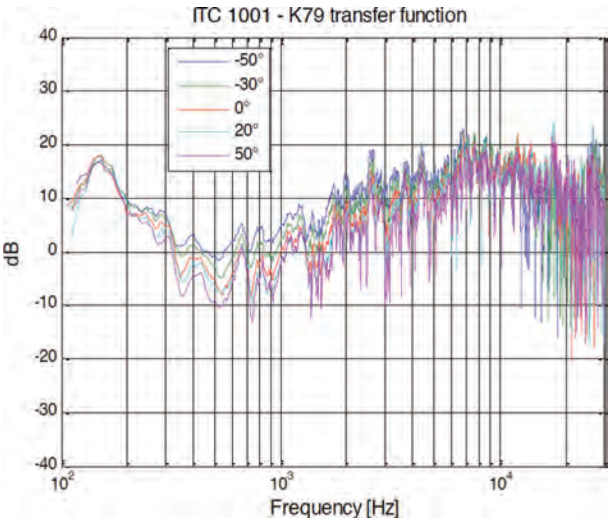


Figure 21 Example of transfer function from Tani et al. (2015)

Influence of air content. One important aspect when performing cavitation noise measurements is the influence of air content. The air content in cavitation test-facilities can influence the radiated noise measurements by three mechanisms. First, the air content has an influence on the nuclei and thereby on cavitation inception. This is discussed in detail by the 23rd ITTC Specialist Committee on Water Quality and Cavitation (2002). Second, the air content will have an influence on the amount of non-condensable gas in the cavity which influences the collapse. Third, at high air content the sound propagation in the facility will be influenced by the air bubbles. Some example studies are discussed next. Lovik (1981) shows that the gas content has a significant influence on the high frequency region where the noise decreases with f^{-2}(above 1-10 kHz for ship scale). The noise levels reduce by about 35 dB when the total gas content increases from 20% and 60%. At lower frequencies the influence of the total gas content is small. It is stated that the cause for the large reduction is the increase of non-condensable gas in the cavitation and that the influence of free gas content on the attenuation is only a few dB. Ikebuchi (1984) shows that for a smooth blade the noise levels increase when the gas content is increased from 77% to 131% and decrease when the gas content is further increased to 191%. If leading edge roughness is applied on the blade, the influence of the air content is very small. Kamiirisa (2001) shows that the cavitation noise levels above 5 kHz decrease to the non-cavitating noise levels when the air content is increased from 70% to 100% while there is no change between 40% and 70% gas content.

Bark (1985) shows that the low frequency broadband hump of pressures measured on the hull becomes a bit more narrow which is in better agreement with full scale data if a gas content of 70% is used instead of 40%. However, if the measurements at 70% gas content were performed at low tunnel speed, the high frequency noise levels are significantly reduced.

It is remarked that some facilities, such as the French large cavitation tunnel GTH, have a separate nuclei injection system. Nuclei are only injected in the area of the propeller and the gas content is kept at a very low level (30%). The influence of gas content on propagation can be taken into account by measuring the transfer function at the flow speed and the gas content at which the propeller noise measurement is performed, but this is not an easy task

Reynolds number effects. The third update in the guideline is dealing with the Reynolds effect on vortex cavitation simulation at model scale, see also Section 4.5. In order to accurately predict the radiated noise of a propeller, it is important to know that the cavitation extent for the operating conditions of the propeller is correctly simulated at model scale. For tip vortex cavitation, the scale effect on cavitation inception is such that this type of cavitation is occurring earlier at full scale than at model scale for the same operating condition defined by (s, K_T). That is why it is recommended to determine if vortex cavitation is present at full scale. For that purpose, a cavitation inception diagram (s, K_T) should be generated of the model scale and full scale propeller as described in ITTC procedure 7.5-02-03-03.1. As discussed in section 4.5, the cavitation number at model scale can be reduced in order to have similar cavity extent as at full scale. However, the cavitation number at model scale can only be reduced for isolated vortex cavitation, Figure 22, and it should not lead to the appearance of other cavitation patterns such as sheet or bubble cavitation that typically generate more noise than vortex cavitation. For situations where for instance sheet cavitation occurs before vortex cavitation at model scale, Figure 23, there is a speed regime of which the cavitation pattern cannot be reproduced at model scale.

Scaling. The fourth update is about the scaling method of the Sound Pressure Level measured at model scale after being corrected for background noise, distance normalization and wall reflection. The two scaling methods that are mainly used by the ITTC organizations are the ones presented in the Section 4.6 and based on equations (3) and (4).

8.3 Uncertainties

The acoustic measurements and cavitation radiated noise should be reported with some idea of the uncertainties that can be expected for the tests. The uncertainty assessment methodology should inform about:

- measurement systems.
- sources of uncertainty considered.
- actual data uncertainty estimates.

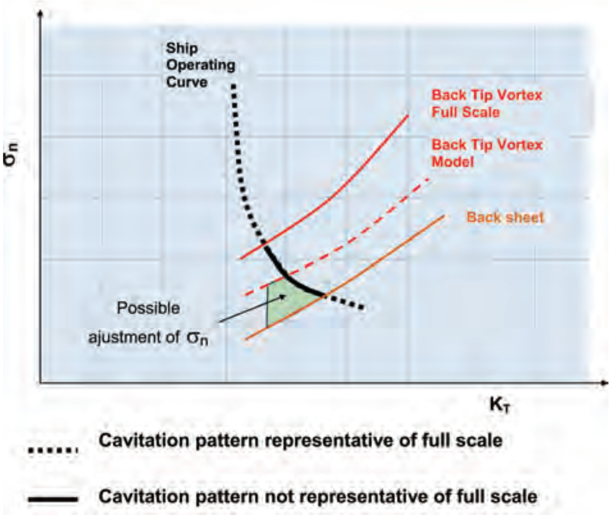


Figure 22 Cavitation inception diagram with isolated vortex cavitation at model scale

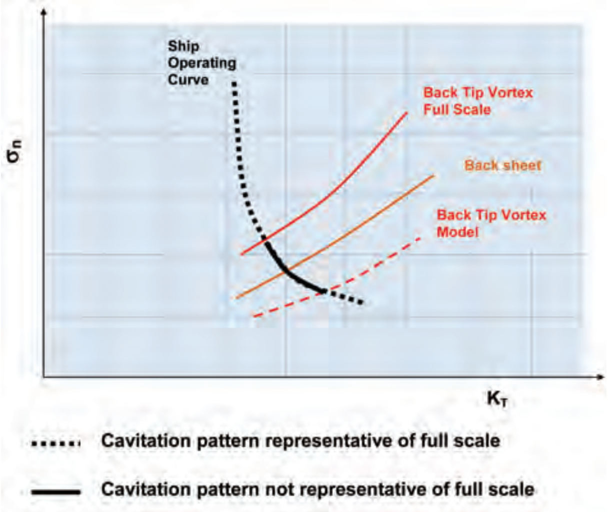


Figure 23 Cavitation inception diagram with no isolated vortex cavitation at model scale

The uncertainty analysis should be done in accordance with the ISO documents on uncertainty analysis, ISO (1992), ISO (1993a) and ISO (1993b) and ITTC procedure 7.5-02-01-01

From the questionnaire launched during the 28th ITTC, the primary sources of uncertainties are the instability of cavitation (especially if operating conditions are close to inception point), the noise scaling, and the wake field. Results of the 28th ITTC questionnaire indicated that the expected uncertainty for the model scale measurement results is 3 to 5 dB and for the scaling procedure also 3 to 5 dB giving a total uncertainty of 5 to 7 dB. Presented data on benchmarking results in Section 10 and full scale model scale comparison presented in Section 9 give some support to these numbers with the remark that the total uncertainty might also include an uncertainty of the full scale measurements. Results on uncertainty of measuring the facility transfer function are given by Tani et al. (2015). Typically, the repeatability is very good but results were shown to depend on the applied sound projector which needs to be further investigated.

9 COMPARING MODEL SCALE WITH FULL SCALE NOISE MEASUREMENTS

The accuracy by which model scale measurements can predict cavitation noise at full scale can be determined from a comparison between model scale predictions and full scale noise measurements. However, many aspects are of importance for a fair comparison between these two measurements and in the following we will review them. Most of the aspects are discussed in detail in other parts of the report so the focus is on providing an overview.

For the prediction of cavitation noise from model scale tests, the following aspects need to be considered:

(1) The ship wake field determines the change in loading on the propeller and thereby the cavitation dynamics. It needs to be set as close as possible to full scale but the validity can only be evaluated by computations which have their own limitations.

(2) The mean propeller loading is obtained from propulsion test results and can accurately be prescribed and measured in the tests. The change in loading is determined by the wake field and therefore less controlled and is usually not measured.

(3) The cavitation extents and dynamics are controlled by propeller loading discussed before and cavitation number. The cavitation number can accurately be prescribed in model scale facilities but adjustments with respect to full scale are applied to correct for change in hydrostatic pressure variation, stern wave height and facility experience. The inception of vortex cavitation is delayed in model tests due to a lower Reynolds number and this can be circumvented by reducing the cavitation number. The type, extent and dynamics of cavitation should be checked by (high speed) video observations. Inception of cavitation is influenced by nuclei and dissolved gas content and is not always well controlled.

(4) The noise measurements can be performed accurately with hydrophones if they are regularly calibrated.

(5) The noise measurements should be corrected for background noise of the facility and propeller driving train such that the resulting noise levels represent cavitation noise only. The correction procedure is well defined but the background noise levels have an uncertainty due to for instance reduced bearing loading if the propeller is replaced by a dummy.

(6) The measured noise levels should be corrected for propagation loss due to facility reverberation and spreading loss such that they represent source strength levels. The propagation loss should be determined using a transfer function measurement.

(7) The model scale noise levels need to be scaled to full scale levels. Two different theoretical formulations are in use giving somewhat different results of which one seems more appropriate for low frequencies and the other for high frequencies.

For the assessment of cavitation noise

from full scale tests, the following aspects need to be considered:

（1） The condition of ship and propeller need to be known with respect to fouling, the propeller is preferably cleaned before the sea trial to avoid the occurrence of cavitation due to fouling.

（2） Ship draft and trim is important as it influences the ship wake field

（3） Sea state and current are of importance for the loading of the propeller. Rudder motions should preferably not be applied in the time window where the noise measurements are performed.

（4） The shaft rotation rate, ship speed and shaft power should accurately be measured such that the propeller operating point, power and cavitation number can be determined.

（5） The propeller is preferably observed by video cameras to check the type and extent of cavitation.

（6） The adopted noise measurement procedures should be described, measurements in beam aspect are preferred as they produce the highest propeller noise levels.

（7） The radiated noise levels need to be corrected for propagation loss, including Lloyd-mirror effect, to obtain source levels.

（8） The ship radiated noise levels contain distributions from various noise sources but are usually dominated by machinery noise and cavitation noise. A distinction between machinery noise and cavitation noise can be made by checking the frequencies of tonals in a narrow-band spectrum and by checking the speed dependency.

A few papers have compared model scale cavitation noise measurements with full scale ship noise measurements.

Examples of validation studies published some time ago are Van der Kooij and de Bruijn (1984) and Bark (1985). Typical differences between model scale and full scale noise levels are 5 dB.

Frechou et al. (2004) present a comparison of full scale radiated noise measurements for a surface ship for non-cavitating conditions with model scale measurements of non-cavitating propeller noise in the large cavitation tunnel GTH. The model scale measurements were performed at the same velocity as at full scale and the noise levels were corrected for change in dimensions. The comparison of levels shows that at 15 knots the non-cavitating propeller is an important contributor to the ship signature.

Seol et al. (2015) compare noise measurements in the KRISO large cavitation tunnel with sea trial data for a 174 m bulk carrier. Above 500 Hz the comparison of the mean noise levels is very good (data given up to 4 kHz) with maximum differences up to 5 dB except for the frequency where singing was occurring on the model scale propeller which was not detected in the full scale data. Below 500 Hz the model scale measurements over predict the noise levels with maximum difference of approximately 15 dB at 55 Hz.

Tani et al. (2016) compare noise measurements for two conditions in the UNIGE medium size cavitation tunnel and the SSPA large cavitation tunnel with sea trial data for a 116 m oil and chemical tanker （M/T Olympus） obtained in the AQUO project. The ship is driven by a single controllable pitch propeller. Each facility shows good agreement for one condition (difference within 5 dB) but differences up to 10 dB or more for the other condition. A transfer function was only determined for the medium size cavitation tunnel and this improved the correlation with full scale for one condition but gave larger differences for the other condition.

Aktas et al. (2016) compare noise levels for three conditions in the medium size cavitation tunnel of Newcastle University with sea trial data for a 19 m. small research vessel of Newcastle University (Princess Royal) obtained in the SONIC project. The noise transfer function was not determined. The correlation at frequencies below 200 Hz is good (typically within 5 to 10 dB). At higher frequencies the noise levels are somewhat under predicted by approximately 10 dB. At these frequencies the signal-to-noise ratio becomes more problematic.

Lafeber & Bosschers (2016) compare noise levels for three conditions in the Depressurized Wave Basin (DWB) of MARIN with sea trial data for a 19 m small research vessel of Newcastle University (Princess Royal) obtained in the SONIC project. The model scale measurements were corrected with a transfer function which was dominated by the Lloyd-mirror effect. For some frequency ranges the agreement between model scale and full scale is very good (within 5 dB), but for other frequencies differences as large as 10 dB are obtained. In Lafeber et al. (2017) DWB predictions for a combifreighter with a single controllable pitch propeller are compared with full scale noise measurements for three pitch angles. Good agreement is obtained in general (within 3-5 dB) but some frequencies, which vary with pitch angle, show differences as much as 10 dB

Summarizing, full scale noise levels can be predicted within 5 to 10 dB by model scale tests. Issues for model tests are signal-to-noise ratio and application of transfer functions. Detailed observations of full scale cavitation extents are often lacking. This makes it difficult to judge if differences are due to wake field, propeller operating conditions or water quality which influence cavity extents or if differences are due to acoustic effects only. It should also be kept in mind that the uncertainty of full scale noise measurements is 4 to 7 dB.

10 BENCHMARKING TEST CASE

The Committee was asked to investigate and define a benchmarking test case for noise measurements in model scale, where the full scale noise measurements are available, but is noted that there is also a need to validate numerical noise predictions. The Committee has found some interesting cases from recent EU projects and past ITTC benchmarking exercises.

The following benchmarking test cases of propellers from open water to noise measurements have been carried out by the ITTC community and other organizations:

(1) Comparative induced-hull pressures and noise measurements with Sydney Express propeller organised by 16th ITTC Cavitation Committee and participated by HSVA, Kamewa and Kryloff (ITTC, 1981). In the 17th ITTC additional noise measurements with the same propeller were performed by HSVA, SSPA, Newcastle, Kamewa, NEYRTEC and Kryloff (ITTC, 1984). Results are presented in Figure 24.

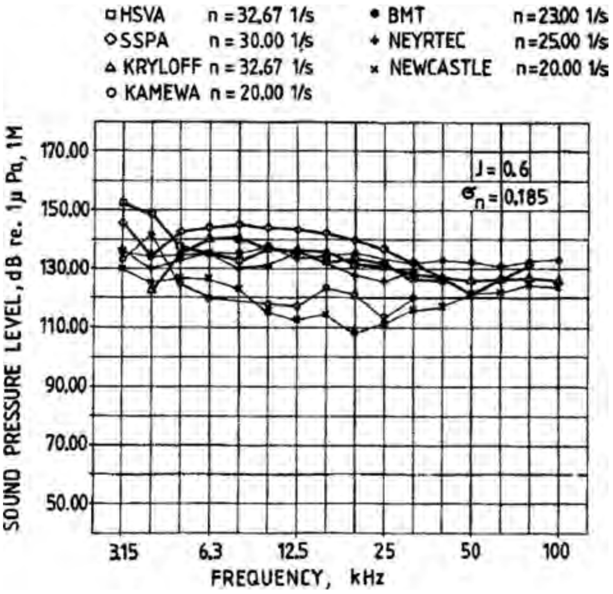


Figure 24 Results of noise measurements with the large (375 mm) Sydney Express propeller (ITTC, 1984)

(2) The 18th ITTC Cavitation Committee continued the comparative induced hull pressure measurements of Sydney Express propeller in model-scale and compared the model test results with full scale values. The committee also continued the model noise measurements in

model scale (ITTC, 1987), but now with a smaller propeller, Figure 25.

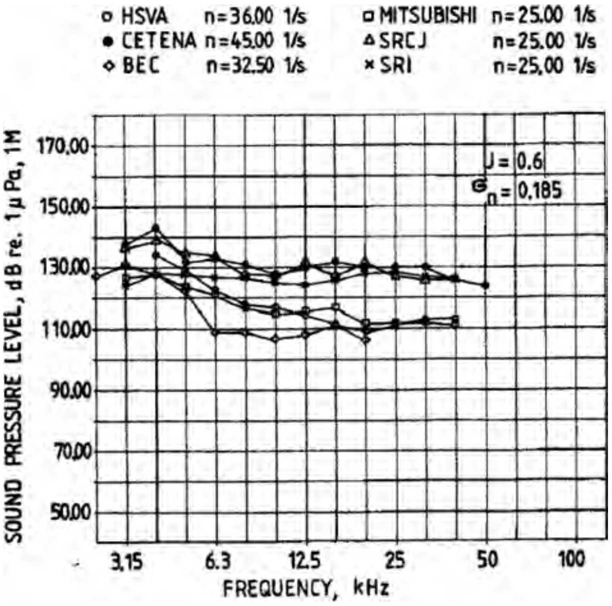


Figure 25 Results of noise measurements with the medium (250 mm) Sydney Express propeller (ITTC, 1987)

(3) A test-case that is used often for validation purposes is the training ship ‘Seiun-Maru’ equipped with a conventional propeller (CP) and highly skewed propellers (HSP I & II), performed in Japan in 1982. The dataset includes high frequency hull pressure measurements, Figure 26. The measurements were made in both model and full scale (JSRA, 1983 & Ukon, et. al., 1991).

(4) The Princess Royal Noise Data: Newcastle University’s Research Vessel, a small catamaran, has a 5 bladed propeller with Wageningen B sections and extensive noise data were measured at full scale and model scale in the SONIC project (Humphrey, et al., 2015; Lafeber and Bosschers, 2016; Aktas et al., 2016a), Figure 27. A round robin test campaign with the same propeller used in the SONIC project was performed by Hydro Testing Forum (HTF) by varying inclined shaft in open water condition to compare the measured underwater radiated noise data obtained from different test facilities (Aktas et al., 2016b), Figure 28.

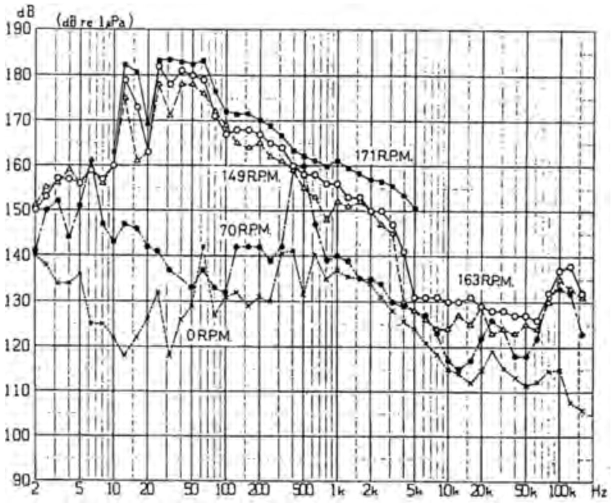


Figure 26 Full scale noise measurements of Sein-Maru with conventional propeller (CP) (JSRA, 1983)

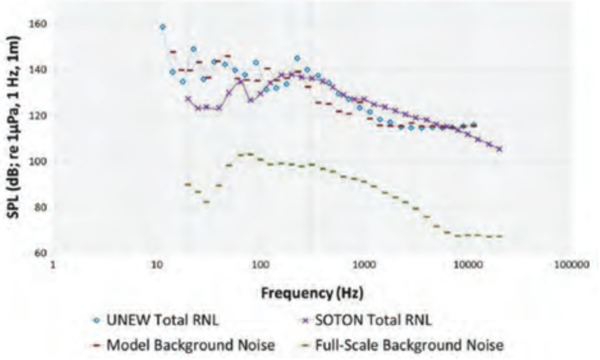


Figure 27 Comparison of total radiated noise levels from full-scale trials and tunnel test measurements based on extrapolations (Aktas et al., 2016a)

(5) A recent comparison of noise measurements of an oil/chemical tanker (M/T Olympus) propeller in model and full scale has been carried out in the EU AQUO project (Hallander and Johansson, 2015; Tani et al., 2016).

The Symposium on Marine Propulsion SMP has organized two workshops for numerical code benchmarking and validation. SMP2011 considers a propeller in open water and SMP2015 a propeller with a shaft inclination angle put in the cavitation tunnel of SVA, Potsdam, Germany, www.sva-potsdam.de/smp15-propeller-workshop/ . The validation data

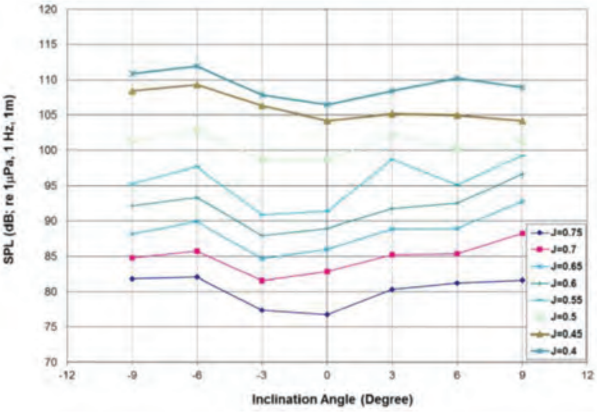


Figure 28 Comparison of noise levels at 6.3 kHz for varying shaft inclination angles and advance coefficients (Aktas et al., 2016b)

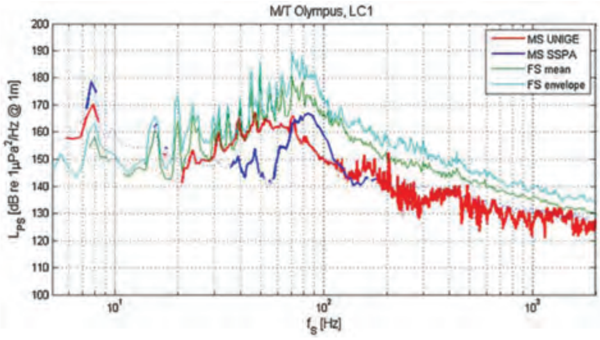


Figure 29 Comparison of noise measurements of model scale with those of full scale (Tani et. al., 2016)

includes pressure pulses but no radiated noise.

Lloyd's Register has made full scale data available for a blind CFD benchmarking workshop which was organized in November 2016. The analysis included ship propulsion data and propeller cavitation extents but did not include hull pressure fluctuations and underwater radiated noise.

Based on the literature survey, possible candidates for benchmarking tests are given in Table 6 and Table 7. A survey within the ITTC community with nine respondents showed that the AQUO vessel received the highest score followed by the SONIC test-case.

Table 6 Review of benchmarking candidates

Test Options	Reference	Propeller Type	Model Scale Noise Data	Full Scale Noise Data	Score (0-5)
1a	SONIC EU Project *The Princess Royal* 19 m Catamaran Research Vessel of UNEW	FPP	A	URN, HPF	3.67
1b	*The Princess Royal* propeller with inclined shaft	FPP	A	-	3.75
2a	Seiun-Maru 105 m Single Screw Training Ship, Japan.	FPP	A	HPF	2.00
3	AQUO EU Project Oil/Chemical Tanker with Single Screw Propeller*	CPP	A	URN	4.33

A: Available, N/A: Not available, URN: Underwater Radiated Noise, HPF: (High Frequency) Hull Pressure Fluctuations.

* : The geometry of the propeller for the chemical tanker is not available to the ITTC as a whole, but can only be made available to individual organizations, provided there is no conflict of interest with the manufacturer (Wärtsilä).

Table 7 Main particulars of propellers *

Test Options	Diameter (m)	P/D	A_E/A_0	Z	Skew Angle (°)
1a & 1b	0.75	0.847	1.057	5	19
2a	3.6	0.95	0.65	5	45
2b	3.6	0.95	0.65	5	10.5
3	4.8	0.87	0.45	4	-

* :Propellers la & 1b cases rotate outward direction, 2a & 2b are right-handed, while 3 is left-handed.

11 SUMMARY AND CONCLUSIONS

11.1 Guidelines

A questionnaire on model scale and full scale noise measurements was issued among ITTC-members and other companies involved in full scale noise measurements. The response showed that both guidelines are well received and it provided very useful information on performing noise measurements which has been used to update the guidelines. It showed that most organizations follow or partly follow the

ITTC guidelines for model scale noise measurements. The model scale guideline has been updated with, among others, a description of transfer function measurements to improve the noise predictions at low frequency. Procedures for full scale noise measurements have been developed (and are in development) by ISO and classification societies which are being followed by respondents to the questionnaire. The updated ITTC guideline for full scale measurements does not aim to compete with these procedures but it is more descriptive in nature. It discusses available noise measurement procedures and provides additional information using for instance ITTC experience on sea trials and information relevant for cavitation noise measurement.

11.2 Scale Effects

Scale effects for the prediction of hydroacoustic noise sources in general are described briefly while those for cavitation noise are described in more detail. Some of these effects are related to the dynamics of the cavitation process on the propeller and are therefore similar as scale effects on e.g. hull pressure fluctuations. Scale effects that are specific for underwater noise involve noise propagation at full scale, reverberation in model scale facilities and the scaling of noise spectra from model scale to full scale. The delay in model tests of the inception of vortex cavitation can be problematic for the prediction of cavitation noise. This topic is also discussed but no established procedure is available.

11.3 Full Scale Noise Prediction from Model Scale Tests

A review has been made of the various aspects of model scale and full scale noise measurements that need to be considered when comparing results of model scale cavitation noise measurements with those of full scale. An important aspect is to isolate cavitation noise from background noise at model scale and distinguish between cavitation noise and machinery noise at full scale. Published papers on correlation between model scale measurement and full scale measurements show results that vary from good agreement (difference smaller than 5 dB), acceptable agreement (difference smaller than the combination of model scale and full scale uncertainties which is estimated at 7-10 dB, the larger number corresponding to low frequencies), and marginal to poor agreement for larger differences. However, these larger differences may also be caused by different cavitation extents on the propeller caused by e.g. differences or uncertainties in operational conditions or other noise sources on the ship during the sea trials. Based on the review it can be expected that properly scaled model scale measurements will result in a prediction of full scale levels with 5-10 dB if proper attention is given to the procedures and conditions for both the model and full scale measurements.

11.4 Uncertainties and Variability

Uncertainties of full scale noise measurements are discussed in several publications providing numbers for both uncertainty and repeatability. The most important aspects are hydrophone location (related to Lloyd mirror effect for low frequencies) and water depth which is influencing propagation loss. Reported uncertainties for full scale noise measurements vary between 4 and 7 dB, where the higher number applies to low frequencies in shallow water. Results of the ITTC questionnaire indicated that the expected uncertainty for the model scale noise levels is 3 to 5 dB. These numbers need to be added with the uncertainty due to noise scaling to arrive at full scale source levels. A review is given of aspects related to the uncertainty for model scale measurements. Uncertainties in model scale measurements are considered to be related to wake field, water quality, cavitation dynamics, especially near cavitation inception, the reverberation of the test facility at low frequencies and noise scaling.

There is a lack of data in the open literature on the influence of operational conditions and variability between sister ships. The influence of manoeuvring on cavitation noise levels is discussed in one publication and it is shown that, on average, a linear relation exists between change in noise levels and ship turn rate. The influence of operational conditions on cavitation inception is shown for one ship. This information can, in a qualitative manner, also be used to consider the influence of operational conditions on cavitation noise.

11.5 Full Scale Noise Measurements in Shallow Water

Noise measurements in ‘acoustic shallow’ water are characterized by a more complicated propagation loss than for deep water. The propagation loss is strongly influenced by reflections off the bottom and the free surface. Methodologies for noise measurements in shallow water have been proposed by Bureau Veritas in its noise rule and NPL in its noise measuring guidelines (Robinson et al., 2014). An ISO standard on this topic is in development by a working group on shallow water measurements. Advanced methods to determine the propagation loss include using a towed acoustic source or using propagation loss modeling that requires knowledge of the variability of the sound velocity with water depth and sea bottom bathymetry.

11.6 Overview Regulations and Standards

New international measurement standards have been issued by ISO while standards on shallow water measurements are in development. In addition to DNV-GL, Bureau Veritas and RINA have also issued a rule on noise measurements that includes limits on noise levels. At present, there are no specific international regulations on underwater noise. In the EU guidelines are being developed on noise monitoring for the assessment of the state of marine waters which is required to achieve and maintain Good Environmental Status in European Seas. Noise monitoring implies that the underwater noise at a specific location is continuously measured to assess the contribution of impulsive and continuous anthropogenic noise sources where shipping is regarded as an important contributor to the continuous noise. In Canada, two harbors now provide a harbor fee reduction for ships that comply with an environmental noise rule of the classification societies.

11.7 Numerical Prediction Methods

A review has been given of numerical prediction methods for propeller generated underwater noise and its propagation. Next to semi-empirical methods, significant progress has been made in the prediction of hydroacoustic noise using CFD to detect the hydrodynamic sources of sound and the Ffowcs Williams-Hawkings equations (FWH) to predict far field radiated sound. Several papers have used this approach to compute the underwater radiated noise due to propeller cavitation up to frequencies of approximately 200 Hz. Results are promising but further research in solving the FWH is necessary on for instance the end cap of the control surface in the permeable approach and on the contribution of non-linear terms. A variety of noise propagation methods are available that compute the far field noise, which is affected by sound speed profile of water, bathymetry, sea state, bottom sediments and the frequency.

11.8 Benchmarking

Benchmarking tests for model scale noise measurements have recently been carried out in several international projects and the Committee has checked the interest in these benchmarking tests within the ITTC. Most interest is in the oil/chemical tanker, driven by a single controllable pitch propeller, tested in the EU AQUO project at full scale and in two cavitation tunnels. However, the geometry of the oil/chemical tanker and its propeller used in the AQUO project cannot be made available to the whole ITTC community but permission can only be granted to individual organizations. Significant interest was also in the small research vessel of Newcastle University, UK, tested in the EU SONIC project at full scale and multiple cavitation test facilities. The public release of the ship geometry is still under consideration. Within the Hydro Testing Forum (HTF) the same propeller used in the SONIC project is tested with inclined shaft in open water conditions for comparison of underwater radiated noise data obtained in different model basins. The geometry of this propeller is public. Also, noise measurements of the training ship 'Seiun-Maru' performed in Japan in 1982 may be used for benchmarking without any restrictions. However, for this vessel noise measurements were only performed using hull mounted hydrophones and no radiated noise measurements are available. Other candidates for ITTC benchmarking were also investigated but not found suitable. Finally, it is remarked that there is also interest in computational analysis of benchmarking cases.

12 RECOMMENDATIONS

The 28th Specialist Committee on Hydrodynamic Noise recommends adopting the following guidelines:

- 7.5-02-01-05: Model Scale Noise Measurements
- 7.5-04-04-01: Underwater Noise from Ships, Full Scale Measurements.

The recommendations for future work are:

- Monitor progress on shipping noise measurement procedures for shallow water and regulations as developed by ISO, classification societies and regulatory agencies.
- Monitor progress on model scale noise measurements with emphasis on facility reverberation and scaling of vortex cavitation noise.
- Monitor progress on computational prediction of propeller noise with emphasis on methods using the acoustic analogy such as coupling CFD with FWH.
- Continue with the definition and conduction of a benchmarking case for validation of the underwater radiated cavitation noise using model scale measurements and computational tools. Most interesting candidates are the oil/chemical tanker of the AQUO project and the research vessel of the SONIC project.
- Evaluate uncertainties associated with model scale noise measurements of cavitating propellers, for instance using the results of the benchmarking tests.

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APPENDIX 1 : MODEL SCALE NOISE MEASUREMENT QUESTIONNAIRE

1.0 - Responder Information: 13 organizations

Organization	Country	Facility type
Hyundai Heavy Industries	South Korea	Medium size cavitation tunnel
Istanbul Technical University	Turkey	Medium size cavitation tunnel
MARINTEK	Norway	Medium size cavitation tunnel
Newcastle University	United Kingdon	Medium size cavitation tunnel
MARIN	Netherlands	Depressurized Wave Basin
DGA Hydrodynamics	France	Large cavitation tunnel
SSPA	Sweden	Large cavitation tunnel
Mitsubishi Heavy Industries, Ltd.	Japan	Medium size cavitation tunnel
Korea Research Institute of Ships & Ocean Engineering (KRISO)	South Korea	Large & Medium size cavitation Tunnels
Schiffbau-Versuchsanstalt Potsdam GmbH	Germany	Medium size cavitation tunnel
Università degli Studi di Genova	Italy	Medium size cavitation tunnel
China Ship Scientific Research Center	China	Large cavitation tunnel
Krylov State Research Centre	Russia	Large cavitation tunnel

2.0 - Procedures and Guidelines for Model-Scale Hydrodynamic Noise Measurements:

- *Model-Scale Procedures and Guidelines*

	Question	Answer *	Details of the answers
2.1	Do you think you will follow this Procedures & Guidelines ?	11 Y ; 1 N ; 1 Y/N	
2.2	Do you think this Procedures & Guidelines is or will be helpful ?	13 Y	
2.3	If you think this Procedures & Guidelines will be helpful, please state why ?		Guidances for institutions ; state of the art ; standardization ; physical problem to take into account
2.4	If you will not follow this Procedures & Guidelines, please state why ?	2A	Noise measurements in DWB (MARIN) ; hydrophone position hard to follow (MHI)
2.5	List what in the guidelines you think is incomplete and should be expanded on ?	9A	Air content level recommendation ; data analysis procedure ; background noise, near field and reverberation corrections ; noise scaling method (TVC, exponent of formula 3,1)
2.6	List what information is missing and should be included in the guidelines.	5A	Calibration procedure ; reverberation corrections ; noise absorption by free nuclei ; propeller model installation (?)
2.7	List any recommendations you have for improving these Procedures and Guidelines	3A	Reverberation assessment procedure ; use of transfer function ; feedback from full scale measurements
2.8	List other ITTC Procedures and Guidelines that you use as part of your Model-Scale testing protocol	11A	Model scale cavitation test (7,5-02-03-03,1); Description of cavitation appearances (7,5-02-03-03,2); propeller model accuracy (7,5-01-02-02) ; cavitation induced pressure fluctuations, model scale experiment (7,5-02-03-03,3); experimental wake scaling methods (7,5-02-03-02,5)
2.9	Do you think the noise Procedures & Guidelines is consistent with other ITTC guides	12 Y	
2.10	If you think there are conflicts between this and other ITTC Guidelines, please state where/how	1N	

**Number under Answer is number of responses; (2Y ; 3N) means 2 responses stated 'Yes', 3 responses stated 'No'; 2A means 2 Answers*

3.0 - Model-Scale Hydrodynamic Noise Measurements :

- *General Information*

	Question	Answer	Details of the answers
3.1A	What is the purpose or customer for testing ? Commercial – Government - Research - Other	13 A	Commercial : 10 Government : 9 Research : 11 Other : 2 (Teaching purpose)
3.2	What is goal/objective of testing ? Support prediction of at-sea performance of configuration being modeled - Comparison of signatures for different configurations - Identification of potential acoustic issues - Other	13 A	Support prediction of at-sea performance of config, being modeled 12A Comparison of signatures for different configurations 11A Identification of potential acoustic issues 10A Other (teaching, research, development ship noise meas.) 2A
3.3	Please state how protocol for acoustic testing is selected / determined	9 A	In house experience 5A ITTC 2A Customer specification 2A
3.4	Please state how OTHER testing protocols are selected / determined	10 A	Thrust/Torque identity + cavitation number (7.5 - 02 03-03.1) 10A

- *Testing*

	Question	Answer	Details of the answers
3.5	Flow speed (range of speeds; xx m/s-- to -- yy m/s)	12 A	Minimum : 2m/s - 6 m/s Maximum : 4m/s - 10m/s
3.6	Please state how these flow speeds are selected (scaled, range of facility, etc.).	12 A	Trade of between Maximum RPM (instruments) / Maximum Va in cavitation tunnel to achieve the highest Reynolds number Froude similarity in DWB
3.7	Please state the increments of flow speed for which measurements are made	7 A	0,1m/s 3A
3.8	Shaft/propeller RPM (range of RPM; xx RPM -- to -- yy RPM).	7 A	Minimum : 120rpm - 1500rpm Maximum : 1200rpm - 3000rpm

	Question	Answer	Details of the answers
3.9	Please state typical model-scale propeller diameter (in mm) for which the prior speed/RPM information was provided.	12 A	Minimum : 200 mm Maximum : 280 mm
3.10	Please state how shaft/propeller RPMs are selected (advance coefficient, thrust/torque, etc.)	11 A	Thrust / Torque identity : 9 Advance ratio : 2
3.11	Please state the increments of shaft/propeller RPMs for which measurements are made.	6 A	either deltaJ ≈ 0,05 or 0,1-0,5rpm
3.12	If multiple testing conditions/configurations are run, what is purpose of testing : Determine cavitation inception - Understanding noise characteristics - Other	13 A	Determine cavitation inception : 10 Understanding noise characteristics : 9 Other (different operating conditions ; sensitivity investigation) : 6
3.13	If only a single condition is tested, what is that condition?	10 A	ship operating condition from customer's requirement
3.14	Do you follow specific procedures in Model-Scale testing to account for scaling of tip vortex cavitation noise	13 A	Yes : 5 No : 8
3.15	If you do follow procedures to account for scaling of tip vortex cavitation noise please briefly describe the procedures.	5 A	Mc Cormick Law scaling law for the cavitation number 18th ITTC cavitation committee report
3.16	Regarding hydrodynamic noise scaling procedures, do you use the same scaling law for conditions close to cavitation inception as for conditions for fully-developed cavitation? If not, please describe the scaling law that is used. Please reply Yes or No and if No, please briefly describe.	11 A	Yes : 7 No for TVC : 4 (Reynolds scaling effect to take into account)
3.17	If you can provide information on influence of wakes, please provide reference or contact information.	5 A	Several papers are listed

	Question	Answer	Details of the answers
3.18	Do you consider/evaluate the influence of air content on noise measurements	7 Y - 6 N	
3.19	If you can provide information of air content, please provide reference or contact information.	7 A	Very few values of air content are given. They are between 30% and 70%
3.20	Do you follow procedures to determine influence of reverberation and to correct for this influence	9 Y – 4 N	A majority is using procedure to correct the influence of reverberation
3.21	If you can provide information on reverberation correction procedures used, please provide reference or contact information.	7 A	4 are determining transfer function.
3.22	Please describe any corrections made to acoustic measurements to account for wall reflections	13 A	No correction : 4 Correction : 9 (some procedure are under development, other are using the transfer function (see 3,21)
3.23	Please describe procedures for correcting acoustic measurements for background noise.	12 A	Propeller replaced by a dummy hub and the test run in the same operating conditions as with the propeller
3.24	If transfer functions are used in acoustic acquisition/analysis, where is the acoustic source positioned when measuring the transfer function (i.e., in propeller plane at 0.7R, etc.)?	11 A	At the location of the cavity on the propeller i.e. mainly around 12 o'clock and between 0,7 R and 0,8 R
3.25	If measurements are made with the source at different locations to provide an 'average' transfer function, please describe the locations where the source is positioned.	6 A	Few location as described before.
3.26	Please describe any difference in procedures for acoustic analysis that are done to account for measurements in the acoustic near-field versus far-field (please describe).	6 A	Near field are not considered. (freq > 1 kHz)

	Question	Answer	Details of the answers
3.27	Please provide information on the range of frequencies covered during testing (lowest and highest frequency) and why the range is determined.	12 A	Freq min : 0,1 Hz – 1 kHz Freq max : 20kHz – 100 kHz Few remarks on low frequency range to be related with the near field and confined environment effects
3.28	What spectral resolution is used for analysis of acoustic test data, why is that resolution selected, and is spectral analysis done using multiple resolutions over the same frequency range? Please describe.	12 A	Narrow band in 1 Hz and in 10 Hz 1/3 Octave band analysis
3.29	Does your testing protocol include addressing narrowband phenomena (discrete, tonal, blade-passage, etc.)? Please reply Yes or No and if Yes, please briefly describe.	13 A	No : 7 Yes : 6 (narrow band spectra include BRF tonals)
3.30	If narrowband phenomena are addressed, how are narrowband measurements scaled in comparison to broadband measurements? Please briefly describe.	5 A	Some different scaling are used for the BRF tonals
3.31	Please describe/state standard uncertainty analysis performed for Model-Scale measurements.	9 A	Organizations are only doing repeat tests (Type A)
3.32	Please describe efforts taken to separate uncertainties from known variability.	8 A	Repeat tests + long record – coherence in the measurement while slightly varying the operating conditions
3.33	Please describe how variability in measurement is handled or accounted for.	6 A	Averaging the repeated measurements
3.34	Please provide your thoughts as to primary source(s) of variability.	9 A	Cavitation instability (close to inception) Scaling Propeller inflow (wake)

	Question	Answer	Details of answers
3.35	If a test conditions is run multiple times to assess variability, please provide below information (note that variability and repeatability are considered the same term): How many times is a condition tested?	11 A	2 => 6 times per operating condition (15 times for one org.)
3.36	If a test conditions is run multiple times to assess variability, please provide below information (note that variability and repeatability are considered the same term): How are multiple tests conducted, i.e. back-to-back, different days, etc. - please explain?	11 A	Back to back : 8 Different days : 3
3.37	If a test conditions is run multiple times to assess variability, please provide below information (note that variability and repeatability are considered the same term): How do you use results from multiple tests (please type Yes in box next to all that apply)? A - Report each separately ; B -Report only average of multiple tests ; C - Other reporting	12 A	A - Report each separately : 3 B -Report only average of multiple tests : 6 C - Other reporting : 3
3.38	What various categories do you divide variability into ? A - Cavitation inception ; B - Setup Configuration ; C - Facility variations ; D – Instrumentation ; E - Variability of source ; F - Other	8 A	A - Cavitation inception : 5 B - Setup Configuration : 6 C - Facility variations : 5 D – Instrumentation : 6 E - Variability of source : 5 F - Other : 0
3.39	What do you consider are the weakest elements in your noise measurement procedures and data analysis (please explain)?	10 A	Cavitation stability (inception) : 1 Confined environment : 5 Background noise : 2
3.40	What test-related issues should the ITTC community pursue (please describe)?	7 A	Round robin test : 3 Correlation between MS and FS : 3 Other : 2

4.0 - Availability of Model-Scale Measurements and Future Efforts

	Question	Answer	Details of the answers
4.1	If you are aware of a case for which testing conditions/geometry and noise levels can be made publicly available and that can be used in a round robin comparison to Model-Scale testing results, please provide contact information.	7 A	Princess Royal case M/T Olympus (EC Project AQUO) IP rights to be overcome PPTC case
4.2	Are you interested in participating in a Model-Scale measurements round robin test-case ?	13 A	Yes : 11 No : 2
4.3	Have you/your organization made comparisons between model-scale and full-scale acoustic measurements? If yes, how many different comparisons have been made?	13 A	Yes : 10 (number of comparisons between 1 & 10) No : 3
4.4	If you/your organization can share results on differences between Model-Scale noise measurements and Full-Scale measurements, please provide contact information to request data.	6 A	4 contacts
4.5	If you can provide a full description of scaling procedures you use to compare Model-Scale measurements to Full-Scale, please describe and provide contact information to get further information.	6 A	ITTC scaling procedure : 4 ITTC 87 : 1 Other : 1

APPENDIX 2 : FULL SCALE NOISE MEASUREMENT QUESTIONNAIRE

	Question	**Details of Answer** *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
1 - Responder Information		
1.1	Responder Name	Nine organizations from eight countries responsed. Completed questionnaires received from: - Korea Institute of Ocean Science and Technology, Republic of Korea - Hyundai Heavy Industries, Republic of Korea - SSPA Sweden AB, Sweden - CETENA S.p.A., Italy - Mitsubishi Heavy Industries, Ltd., Japan - Naval Surface Warfare Center, Carderock Division, United States - Técnicas y Servicios de Ingeniería, S.L, Spain - TNO, The Netherlands - DNV GL, Norway
1.2	Responder Organization	
1.3	Responder Country	
1.4	Responder email address	
1.5	Name/Location of Facilities/Ranges	[3] Organizations have a name and location for a full-scale facility. Most organizations use mobile measurement equipment that can in principal be used anywhere. In most cases the measurements have been carried out in the near seas of the organizations.
2 - Procedures and Guidelines for Full-Scale Hydrodynamic Noise Measurements:		
	Full-Scale Procedures and Guidelines	
	If you have read the recent ITTC Full-Scale hydrodynamic noise measurements Procedures & Guidelines please respond to the below questions.	
2.1	List portions of Procedures and Guidelines that you think are or will be most helpful.	"Overall description of the full scale noise measurement procedures was found to be the most helpful. [1] Uncertainty analysis was the most helpful portion in the procedures and guidelines. [2] The ITTC guidance is covered in ISO, ANSI/ASA and DNV standards.
2.2	What in the guidelines do you think is incomplete and should be expanded on?	[2] Identified uncertainty analysis and repetition as the main incomplete section in the guidelines. [1] Shallow water measurements needs further elaboration. [1] Current content is complete.
2.3	What information is missing and should be included in the guidelines?	[2] Instead of writing ITTC guidelines it would be better to refer to international standards. It would be valuable to give guidance on how to select the most appropriate standard for a particular measurement case. A reference to BV NR 614 class notation was inquired. [1] Satisfied in current state of the guidelines.
2.4	Please provide any recommendations you have for improving these Procedures and Guidelines.	[3] Noted the guidelines are at a general level and do not give additional information compared to the international standards or class notations. It would be valuable to give guidance on how to select the most appropriate standard for a particular measurement case.
2.5	Please list any portions of the Procedures/Guidelines that you think should be changed or deleted.	[6] Did not specify any changes or removable parts in the Procedures/Guidelines. [1] Disagrees with shallow water condition definition being now depth-to-wavelength ratio from 10 to 100. [1] Disagrees there is a consensus on what is meant by ship beam aspect since US navy uses ±15° while ANSI/ASA and ISO uses ±30°. [1] Suggested Guidelines refer to international standards and not to copy parts of the texts in the standards. This way, the ITTC guideline would automatically update itself when the standards are updated.

Question		Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
	Questions regarding use of other standards/guidelines for Full-Scale Hydrodynamic Noise Measurements	
2.6	Please list any other specific National or International guidelines or standards you follow or use for Full-Scale testing.	Most of the organizations follow more than one standard. [5] Follow ISO/PAS 17208-:1 Acoustics - Quantities and procedures for description and measurement of underwater sound from ships, Part 1: General requirements for measurement in deep water. [2] Follow the ISO/DIS 16554.3 Ships and marine technology -- Measurement and reporting of underwater sound radiated from merchant ships -- Survey measurement in deep-water. [2] Follow the ANSI/ASA S12.64-2009/Part 1 (R2014) Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements. [2] Follow the Bureau Veritas Underwater Radiated Noise (URN) Rule Note NR 614 DT R00 E, 2014. [2] Follow the DNV Ship rules Pt.6 Ch.24 SILENT Class Notation. 1] Follow STANAG 1136 Standards for use when measuring and reporting radiated noise characteristics of surface ships, submarines, helicopters, etc. in relation to sonar detection and torpedo acquisition risk, or STANAG-1418 ED.2 Standards for mine warfare acoustic measurement – AMP-15 [1] Follow JRC Scientific and Policy Reports: Monitoring Guidance for Underwater Noise in European Seas Part II: Monitoring Guidance Specifications.(2014) ISBN 978-92-79-36339-9. [1] Follow AQUO European Collaborative Project, deliverable D3.1, "European URN Standard Measurement Method".
2.7	If you follow National or International guidelines or standards please state why you follow the ones that you do.	[2] Customer demand mentioned as reason to follow some particular guideline or standard. [2] Mentioned simplicity, guidelines for uncertainty analyses, and repeatability of the method.
2.8	If you do not follow any guidelines/standards for Full-Scale testing, please briefly explain why.	"[1] Minimum water depth is difficult to satisfy. [1] Organization disagrees with some parts of the standards and have more experience in conducting the measurements."
2.9	If you are not aware of an appropriate Procedures/Standard but one exists or is available, would you possibly follow it?	[1] Yes [1] No
2.10	If there are published Standards/Guidelines that are at least partially followed, please list what is followed.	Following standards and guidelines were mentioned once: - ISO/PAS 17208-:1 Acoustics – Quantities and procedures for description and measurement of underwater sound from ships, Part 1: General requirements for measurement in deep water. - ANSI/ASA S12.64-2009/Part 1 (R2014) Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements. - DNV Ship rules Pt.6 Ch.24 SILENT Class Notation - AQUO European Collaborative Project, deliverable D3.1, "European URN Standard Measurement Method"
2.11	If you have experience on using more than one Guideline for Full-Scale ship underwater noise measurements please list your experience with differences in results following each Guideline	[1] Organization has measured simultaneously same ship with the ANSI/ISO method and DNV/GL method. In that case the correlation was good although the respondent mentioned that the results of the ANSI/ISO methodology depend on the weather conditions.
2.12	If more than one Guideline is used for Full-Scale ship underwater noise measurements, which Guidelines are preferred.	[2] Listed Bureau Veritas Underwater Radiated Noise (URN) Rule Note NR 614 DT R00 E, 2014. [1] Listed ISO/CD 16554, ANSI/ASA S12.64-2009 Part 1 - ISO 17208. [1] Listed DNV GL SILENT.
2.13	Do you think having Procedures and Guidelines for Shallow-Water underwater noise measurements would be helpful?	[8] Yes [1] No

	Question	**Details of Answer** *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
2.14	Considering the complexity of Shallow-Water measurements, do you think meaningful Procedures and Guidelines can be developed (please type Yes or No in below box)?	[7] Yes [1] No
2.15	Please list what you recommend to be included in Procedures and Guidelines for Shallow-Water measurements.	[4] Minimum water depth, minimum distance at closest point of approach, and distance correction methods (propagation loss). [3] References to AQUO project and ISO standard procedures.
	Questions regarding use of other ITTC Procedures and Guidelines as part of Full-Scale testing protocol	
2.16	Please list other ITTC Procedures and Guidelines that are followed as part of Full-Scale testing.	No responses.
2.17	What is reason other Procedures/Guidelines are used?	No responses.
2.18	If other ITTC Procedures/Guidelines are not used, please state why.	The standards or customers have not requested or the full scale measurements have been dedicated only to underwater noise measurements.
	Questions regarding determining Source Level from underwater noise measurements	
2.19	Do you think a single Source Level (for a given operating condition) is adequate and potentially a reliable quantity for characterization of a ship underwater noise emission [Source Level is a measure for the sound radiated into the ocean, independent of the environment (no influence of surface, bottom, propagation/absorption, etc.)]?	"[7] Yes [2] No"
2.20	Please comment on any experience or opinion you have regarding determining Source Level.	Several: Directivity, Lloyds mirror effects and bottom influences were mentioned as a source of uncertainty. Several: Measurement conditions, equipment, processing, and measurement distance to the vessel are a source of uncertainty.
2.21	Do you think "Source Level" is a reliable quantity for comparing different designs?	[8] Yes [1] No
2.22	Do you think "Source Level" is a reliable quantity for assessing impact on the environment?	[7] Yes [2] No
2.23	Please comment on any experience or opinion you have regarding use of Source Level for quantifying ship noise.	It was mentioned that the Source Level should be used as an input for propagation modeling. By utilizing standards, the variability of Source Level in different measurement campaigns can be strongly limited, at least to compare designs and complying the Source Level with rules. Notes were given that there are uncertainties in Source Level determination related to assessment of source and receiver properties, e.g. the depth of the source center. [1] "I do believe that comparing ship classes based on measurements at a consistent geometry and careful averaging approaches which are independent of further modeling, would offer a "yes" to questions 2.21 and 2.22. [1] The Source Level should be determined at one meter of the hull instead at one meter distance of a singular noise source.
	Other questions related to Full-Scale noise testing	

	Question	**Details of Answer** *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
2.24	If you have any papers or reports you can share on the general topic of noise measurements, or ones you can recommend, please provide contact information for getting copies.	The following papers were recommended: - AQUO European Collaborative Project, deliverable D3.3, "On-site measurements-Experimental data for accurate identification and quantification of Cavitation Noise and other sources", 2014. - Johansson, T., Hallander, J., Karlsson, R., LångströmA.andTuresson, M. "Full scale measurement of underwater radiated noise from a coastal tanker" IEEE/MTS OCEANS'15, Genua 2015. - Tani, G. Viviani, M. Hallander, J., Johansson, T. and Rizzuto, E., "Propeller underwater radiated noise: A comparison between model scale measurements in two different facilities and full scale measurements", Applied Ocean Research, Volume 56, March 2016, Pages 48–66, Elsevier, UK. - J. Acoust. Soc. Am., Vol. 107, No. 1, January 2000 P. T. Arveson and D. J. Vendittis: Modern cargo ship noise. - CAF de Jong: 'Characteristics of ships as sources of underwater noise', Proc. NAG-DAGA 2009, Rotterdam. - de Jong et al. 2010 'Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: analysis of source levels and background' TNO-DV 2010 C335, available at http://www.dredging.org/media/ceda/org/documents/resources/othersonline/uwn-tno-dv2010c335.pdf - ECUA 2012, The ship as an underwater noise source, K.A. Abrahamsen, proceedings of the 11th European Conference on Underwater Acoustics - Neil Sponagle, "Variability of ship noise measurements". Defence technical information center 1988. In addition, references to the proceedings of ICSV22, NAV 2015, and OCEANS'15 conferences were given, as well as to public deliverables of AQUO FP-7-EU project.
2.25	What other type of Procedures and Guidelines that relate to Full-Scale testing do you think would be helpful?	[1] Guidelines for tools/methods aimed at assessing the range correction of measured noise levels when spherical spreading is not assumed could be useful
3 - Full-Scale Hydrodynamic Noise Measurements: General Information		
	General Information	
3.1	What is the purpose or customer for testing?	
3.1A	- Commercial (commercial contract requirement)	[7] yes
3.1B	- Government / naval	[7] Yes
3.1C	- Research	[8] Yes
3.1D	- Assess acoustic/seismic operations	[4] Yes
3.1E	- Fishery (research) vessel	[6] Yes
3.1F	- Assess environmental impact	[2] Yes
3.1G	- Other (Please specify in box)	No responses.
3.2	What is goal/objective of testing?	
3.2A	- Measure radiated noise level at a hydrophone-to-ship distance specified by the customer and/or dictated by the range configuration (no corrections made for propagation differing from spreading, surface/bottom, absorption, etc.)	[5] Yes
3.2B	- Determine acoustic source level (accounting for free-surface, range spreading, and absorption)	[8] Yes
3.2C	- Screening - Comparison of ship signature to other ships	[4] Yes
3.2D	- Demonstrate ship meets required specifications	[7] Yes
3.2E	- Other (Please specify in box)	No responses.

	Question	**Details of Answer** *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.3	Please briefly state how your acoustic testing protocol is selected / determined	[3] Follow the customer requirements. [3] Follow specific procedures ([1] AQUO method; [1] DNV GL SILENT procedure; [1] ISO/PAS 17208)"
3.4	If your testing protocol is documented and available for others to read, please provide contact information for getting a copy.	As stated in Q3.3, and more detailed description is in Q2.6. Also following information was provided: - University of Southampton/CETENA paper in the OCEANS'15 Proceedings (Genoa 2015); - CETENA/other organizations paper in the 'Underwater Acoustics (UA2014)' Conference Proceedings."
3.5	If your Full-Scale testing is supported or guided by Model-Scale testing, please describe how.	No responses.
3.6	If Full-Scale performance predictions are made prior to testing, please indicate how.	
3.6A	- Based on scaling of model-scale testing	[2] Yes
3.6B	- Based on analytical/numerical studies	[5] Yes
3.6C	- Based on changes from prior test results	[2] Yes
3.6D	- Other (Please specify in box)	[1] "Based on the onboard hull vibration measurement".
3.7	If Full-Scale predictions are made based on Model-Scale testing please describe scaling used.	[2] Use ITTC scaling law.
3.8	If Full-Scale results are used to guide/update prediction modeling, please explain how	[2] To make correlations between predictions and full-scale measurement.
	Vessel Testing Parameters	
3.9	Ship speed (range of speeds; xx knots -- to -- yy knots).	Depends on ship type and project requirement. Answers are quite scatter, some were in certain range, e.g. 14-20knots, some gave the whole ship speed range, e.g. 0-25knots.
3.10	Ship speed (range of speeds; xx knots -- to -- yy knots).	Depends on ship type and propulsion unit. Typically for research vessel or large commercial vessel, shaft RPM can be in the range 70 rpm-300 rpm.
3.11	What is the typical propeller diameter (in meter) for which speed/RPM range information is provided?	It depends on ship type. The answers were given from the smallest 0.5m to the largest 10m.
3.12	Propulsion power (range of power; xx -- to – yy %MCR).	[4] Depends on requirements, typically from 60% MCR to 100% MCR. [1] Specified 0-to-100% MCR.
3.13	In case of commercial test, if you also test for operating conditions other than requirements, please describe additional conditions in below text box.	[1] For FRV, trawl condition is tested [1] If time allowed, a range of operating conditions from 0 to max power will be tested.
3.14	If acoustic measurements are made for ship operating conditions other than those above, please list conditions.	[1] Static testing of mechanical sources and side thruster noise testing.
3.15	Please indicate reason for testing over multiple conditions.	
3.15A	- Quantify acoustic levels over a range of operating conditions	[7] Yes
3.15B	- Cavitation inception	[3] Yes
3.15C	- Required by acceptance criteria	[6] Yes
3.15D	- Understanding noise characteristics	[6] Yes

	Question	Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.15E	- Other (Please explain in box)	No responses.
3.16	If testing is done at only one setting/condition, please specify condition	[2] Specified at 85% MCR.
3.17	If runs are conducted to help determine specific signature characteristics, please describe.	[1] For NOAA vessels, multiple speeds are tested to isolate speed-dependent noise such as flow, propeller, and prime mover characteristics.
3.18	If runs are made at specific increments of speed/RPM to determine cavitation onset, please state increment.	[1] Specified 2-knot increment onboard test Other specified 3RPM increment for low RPM and 1RPM increment near NCR and MCR.
3.19	Please indicate if special runs are done to isolate specific noise sources. Provide explanation in boxes that apply	
3.19A	- Auxiliary machinery (please describe run configurations)	[1] Stated to do static testing.
3.19B	- Propulsion machinery (please describe run configurations)	No responses.
3.19C	- Propeller (please describe run configurations	No responses.
3.19D	- Other (Please describe source and run configurations in below box)	No responses.
	Test Operating Conditions	
3.20	Please state variation of speed that is considered acceptable for a given test condition.	Six answers were given, and it is case dependent. Answers are from 0.2kn to 1kn. [1] Stated that within 2% around the mean value in the run is considered acceptable.
3.21	Please state variation of RPM that is considered acceptable for a given test condition.	[5] It depends on ship type. The answers are from 0.5RPM to 5RPM. [1] Stated that within 1% around the mean value in the run is considered acceptable.
3.22	Please state the variation of blade pitch setting for a controllable pitch propeller that is considered acceptable for a given test condition.	[2] Stated that once pitch is set, variations are very small and are not taken into account.
3.23	Please specify the variation in Ship Power that is considered acceptable for a given test condition.	[1] Stated that it is just to be monitored. [1] Stated that within 1% around the mean value in the run is considered acceptable.
3.24	Please specify the variation in rudder angle that is considered acceptable for a given test condition.	[2] Recommended to avoid operating rudder during data recording. [2] Specified 1.5 degree and 2.0 degree respectively.
	Please provide information regarding seaway conditions that are monitored during testing.	
3.25	Please state maximum ocean current that is considered acceptable for testing.	[1] Stated that 2 knots is the maximum. [2] Stated that it is not very sensitive to sea currents. [2] Stated that it depends on the project.
3.26	Please state what considerations are given to ocean current direction during testing.	No special considerations of ocean current direction were considered. [2] Stated that in order to average this effect, the alternative directions of the runs/or such kind condition series were considered
3.27	Please state maximum Sea-State level (or Beaufort scale) for which testing is acceptable (please use S.S. ## or B.S. ## for response to distinguish between two scales)	B.S. = 2 or 3, S.S.=2 or 3 were mostly specified.
3.28	If there are sea state restrictions, please select reason for restriction.	

Question		Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.28A	- Acoustic	[5] Yes
3.28B	- Hydrodynamics	[3] Yes
3.28C	- Other (Please specify in box)	"[1] Specified ""Mobile array deployment"".
	Acoustics Testing	
3.29	Please state water depths for which acoustic measurements are made.	
3.29A	- Shallow Water	[6] Yes
3.29B	- Deep Water	[7] Yes
3.29C	- Other (Please specify in box)	No responses.
3.30	For shallow water testing, what is minimum water depth (or range of depths) in meters and are other bottom issues considered?	[2] Stated to follow procedures BV-NR614 / ISO 17208-1. [3] Specified 10-20m, 30m, 40-60m and 100m respectively. [1] Stated that the slope of the bottom and the bottom material are considered.
3.31	For deep water testing, what is minimum water depth (or range of depths) in meters and are bottom issues considered?	[1] Stated to follow procedure BV-NR614. [4] Specified from minimum 150m to maximum 1500m (150m, 400m, 150-500m, 300-1500m respectively).
3.32	Please specify typical depth of hydrophone(s) for acoustic measurements (in meters).	[1] Specified 0.2m, 15m and 30m from bottom. [6] In the range 20m-300m. [3] 'do not know'. [3] 'vary case to case'.
3.33	Please describe bottom conditions at the test range (reply 'do not know' if no survey has not been made).	[1] Described as 'Clay, flat sea bottom at ship lane, gentle slope at hydrophone anchoring position as recommended by DNV'. [3] 'do not know'. [3] 'vary case to case'. [1] Described as 'Clay, flat sea bottom at ship lane, gentle slope at hydrophone anchoring position as recommended by DNV'.
3.34	Please specify typical Closest-Point-of-Approach (CPA) of vessel to array (in meters) during acoustic testing.	Answers were mostly in the range 100m-300m (100m, the larger of 100m or one ship length, 180m, 100-200m, 300m, 155-373m respectively).
3.35	Please describe how test vessel position is tracked during test run past the acoustic array. If GPS is used, please state whether it is a GPS or DGPS system.	[5] DGPS. [2] GPS.
3.36	Please describe the data window over which acoustic levels are averaged to arrive at reported levels (i.e. +/- 30 degrees, etc.).	[2] Specified +/- 30 degrees. [1] Specified +/- 15 degrees. [1] Specified +/- 45 degrees. [1] Specified 1 – 2 ship lengths depending on ship speed.

	Question	Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.37	Please describe range correction method used, when averaging levels, that accounts for differences in range over the length/duration of the averaging window.	In general the samples in 1 second interval within data window were used and range corrected for propagation effects, and then averaged. An alternative way, the 1s samples are power averaged. The PSD of the whole run obtained and then range corrected.
3.38	What range (source-to-receiver distance) corrections for propagation loss are applied to the measured acoustic data?	
3.38A	- Spherical spreading	[4] Yes
3.38B	- Cylindrical spreading	No responses.
3.38C	- None	No responses.
3.38D	- Other (Please explain in box)	[2] Stated that Transmission Loss is measured. [1] Stated that Spherical spreading and absorption were applied.
3.39	Please describe how the source location for range corrections is specified.	[2] Specified at the position between propeller and main engines. [2] Specified at the position where ship acoustic center was assumed or targeted in the description of the test plan. [1] Specified at 0.7 propeller radius when blade is pointing upwards.
3.40	Please describe adjustment made to measurements for surface reflection in reported levels (state none if none are made).	[5] 'none'. [1] Stated to use half spherical spreading.
3.41	Please describe adjustment made to measurements for bottom reflection in reporting levels (state none if none are made).	[6] 'none'. [1] Stated to minus 5 dB.
3.42	Please describe adjustments made for absorption in reporting levels (state none if none are made).	[5] 'none'. [1] Stated to calculate by using Francois and Garrison's formula.
3.43A	- Port and/or Starboard	[8] Yes
3.43B	- Keel aspect	[1] Yes
3.43C	- Other (Please specify in box)	[1] Specified '+/- 45 degrees fore/aft aspect'. [1] Specified 'beam, fwd quarter, stern quarter'.
3.44	Please indicate how Port and Starboard measurements are handled in reporting ship levels.	
3.44A	- Report each separately	[5] Yes
3.44B	- Average and report one level	[4] Yes
3.44C	- Determine if port/starboard differences vary with operational conditions	[3] Yes
3.44D	- Separate Port and Starboard levels are not measured	No responses.

	Question	Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.44E	- Other (Please explain in box)	[1]'to follow customer's demands'
3.45	If measurements are made with multiple sensors, how are multiple sensor results combined for reporting (please describe)?	[2] 'power average'. [2] 'average'. [1] 'Each individual hydrophone is power averaged over time, while 3 to 4 omnidirectional hydrophones are numerically averaged '.
	If in situ calibrations (artificial sources) are performed at the acoustic range to quantify transmission effects, please provide following information.	
3.46	Type of source that is used for calibration.	[1] Use Loudspeaker. [1] Use Gun.
3.47	If calibrations are to quantify spreading loss, how is calibration done and used.	[1] Stated that a number of frequencies 60, 120, 300, 600, 1000 and 10000 Hz were used, and tones were sent at a number of positions along the ship path at propeller shaft depth. [1] Stated that resulting noise was measured at typical measurement situation for CPA.
3.48	If calibrations are to quantify absorption, how is calibration done and used.	[1] Stated just the same as described in Q3.47 (the first one). No other answers were given.
	[In uncertainty analysis a distinction is made between Type A uncertainty (uncertainty evaluated by statistical analysis of a series of observations) and Type B uncertainty (uncertainty evaluated by non-statistical methods). If applicable, please make a distinction between these types of uncertainty in your reply below.]	
	Test Related Measurements and Data Issues	
3.49	Please describe standard uncertainty analysis performed for underwater signature measurements.	Most organizations follow the specific procedures or standards. Procedures AQU0, ISO 17208-1,ANSI/ASA each were mentioned once, while BV was mentioned twice.
3.5	Please describe how uncertainty is accounted for in measurement results.	[2] 'standard deviations and averages were taken of data by long time measurements' [3] 'follow specific procedures as AQU0, BV,ANSI/ASA'
3.51	Please provide your thoughts as to most common source(s) of uncertainty.	The following sources of uncertainty were mostly mentioned: variations in ship operating condition; hydrophone positions; actual acoustic centre of the ship; TL calculation or measurement; residual motion of the hydrophone (array) due to the sea conditions; open circuit voltage sensitivity for hydrophones; acoustic filtering effects at the test site; near field effects in the low frequency region; etc.
3.52	If multiple runs are performed to determine/quantify uncertainty, how many different runs are done?	Three answers were given, and mostly specified 2 to 4 runs. [1] 'perform 3 runs for both STBD and PORT side' [1] 'perform two runs for each condition and four for the reference condition' [1] 'minimum 2 runs at one CPA for large ships'
3.53	If multiple runs are performed to determine/quantify uncertainty, how are results used?	
3.53A	- Report each separately	[2] Yes
3.53B	- Report average of multiple runs	[2] Yes
3.53C	- Report average and spread of multiple runs	[3] Yes
3.53D	- Other reporting (Please describe in box)	No responses.
3.54	What various categories do you divide uncertainty into?	

Question		Details of Answer *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
3.54A	- Do not categorize uncertainty	[4] Yes
3.54B	- Operational conditions	[1] Yes
3.54C	- Environmental	[2] Yes
3.54D	- Instrumentation	[2] Yes
3.54E	- Acoustic source	[1] Yes
3.54F	- Other (Please explain in box)	No responses.
3.55	If your testing protocol addresses source(s) of uncertainty, explain how.	[3] 'follow specific procedures or standards' AQUO/BV,ANSI/ASA,BV-NR614 were mentioned.
3.56	If you add a safety margin to results to take uncertainties into account, please state margin.	No responses.
3.57	If you add a safety margin to results from one measured vessel to account for possible certainty that will occur for a series of similar ships, please state margin.	No responses.
3.58	What do you consider are the weakest elements in your noise measurement procedure and data analysis (please explain)?	The following aspects were mostly mentioned: Estimation of Transmission Loss (spreading + absorption); actual capability to match prescribed operating conditions of the ship; position of hydrophones
3.59	What test-related issues should the ITTC community pursue (please describe)?	[1] 'Prescriptions about range correction and relating in-situ measures if any'
4 - Availability of Full-Scale Measurements and Future Efforts		
4.1	For informational purposes, if you/your organization would be willing/able to provide typical differences in noise levels between sister ships for non-cavitating and/or for cavitating conditions, please list contact information to make request.	[3] Organizations provided POC information.
4.2	If you/your organization can provide examples of acoustic data both as received and converted to source levels, please list contact information to request data.	[4] Organizations provided POC information.
4.3	Have you/your organization made comparisons between model-scale and full-scale acoustic measurements? If yes, how many different comparisons have been made?	[2] Indicated 1 comparison. [3] Did not indicate the number of comparisons. [1] Indicated a number of comparisons.
4.4	If you/your organization can share results on difference between Model-Scale noise measurements and Full-Scale noise measurements, please provide contact information to request data.	[3] Organizations provided POC information. Some referred reports from SSPA Sweden AB: Comparison between model- and full scale for the case of M/T Olympus is presented in Tani et al. APOR 56 (2016). Full scale measurements are presented in more details in [AQUO European Collaborative Project, deliverable D3.3, "On-site measurements-Experimental data for accurate identification and quantification of Cavitation Noise and other sources", 2014]. The model scale tests are presented in more details in [AQUO European Collaborative Project, deliverable D2.5, "Propeller noise experiments in model scale", 2014].

Question		**Details of Answer** *(Note: Number in [ ] is number of responses; [2] means two (2) responses of this type)*
4.5	If you can provide a full description of scaling procedures you use to compare Model-Scale measurements to Full-Scale, please describe and provide contact information to get further information.	[3] Organizations provided POC information.
4.6	If you/your organization have a suitable candidate for which Full-Scale data are available for public review, please provide contact information.	[4] Organizations provide POC information.
5 - Other Information You May Wish to Provide		
5.1	Further Comments regarding Procedures and Guidelines for Full-Scale Hydrodynamic Noise testing.	[1] Recommended ITTC members participate in the ISO and ASA standards meeting for further collaboration to minimize conflicting guidelines across the ship underwater acoustics community. Others suggested the harmonization of the guidelines for full-scale and model scale measurements need to be improved. Such examples as: the frequency bandwidth and resolution differ, the model scale guideline suggests to report the spectral density of the radiated noise, while the full-scale guideline suggests to report the total level in the bands.
5.2	Recommendations on issues the ITTC Hydrodynamic Noise Specialist Committee should pursue.	[1] Recommended to do uncertainty analysis for a measurement of a surface ship using actual measured data from various techniques. [1] Recommended ITTC members be encouraged to support the work in ISO TC43 SC3 WG1.
5.3	Any other comments you wish to provide.	[1] Comment regarding the questionnaire - feeling was that the questions were largely oriented to collect information about specific, 'fixed' measurement systems/procedures. He suggested that in evaluating the answers it should be considered that 'mobile' devices (hardware+software) with 're-configurable' configurations are also in use.