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Report of the Specialist Committee on Cavitation and Noise of the 30th ITTC

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This report summarizes the work of the Specialist Committee on Cavitation and Noise of the 30th International Towing Tank Conference.

1. INTRODUCTION

1.1 Membership and Meetings

The members of the Specialist Committee on Cavitation and Noise of the 30th ITTC are:

- Dr. **Romuald Boucheron** (Chair)
  DGA Hydrodynamics, FRANCE
- Dr. **Francisco Alves Pereira** (Secretary)
  CNR-INM, ITALY
- Dr. **Djahida BOUCETTA**
  GHENT University, BELGIUM
- Mr. **Crispin FETHERSTONHAUGH**
  QinetiQ, UNITED KINGDOM
- Dr. **Przemyslaw KROL**
  (up to 2023)
  CTO, POLAND
  replaced by
- Dr. **Jan HALLANDER** (since 2023)
  SSPA Maritime Center, SWEDEN
- Dr. **Thad MICHAEL**
  NSWC Carderock Division, UNITED STATES
- Dr. **Yezhen PANG**
  CSSRC, CHINA
- Dr. **Cheolsoo PARK**
  KRISO, KOREA
- Mr. **Kei SATO**
  Mitsubishi Heavy Industries, JAPAN
- Mr. **Ville VIITANEN**
  VTT, FINLAND

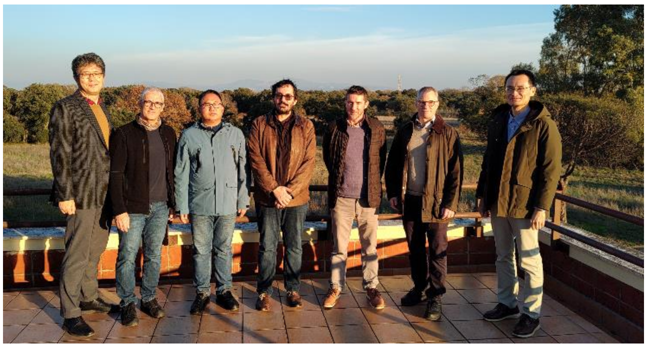

Figure 1: Photograph of the Specialist Committee on Cavitation and Noise at its 3rd in-person meeting in Roma.

The committee held four face-to-face meetings during the work period at the following locations:

- Val-de-Reuil, France at DGA Hydrodynamics on June 15-16, 2022.
- Daejeon, South Korea at KRISO on May 23-25, 2023
- Roma, Italy at CNR-INM on January 30 to February 1st, 2024.
- Wuxi, China at CSSRC on April 23-24, 2024.

Video conferences were held on January 12 and 13, 2022; December 13-14, 2022; November 28-29, 2023, July 15, 2024.

1.2 Recommendations of the 29th ITTC

The recommendations for the work of the Cavitation and Noise Specialist Committee as given by the 29th ITTC were as follows:

1. Review and update the current guidelines on model and full scale noise measurement and review and update the existing procedures on cavitation; provide recommendations for new guidelines / procedures, if any.

2. Review the state of the art on cavitation model testing (cavitation appearance, hull pressure fluctuation, thrust break down, cavitation erosion) with a focus on ways to reproduce the scaling effects on ship wakes. Conduct an Uncertainty Analysis on the full-scale prediction of all the cavitation parameters (cavitation appearance, hull pressure fluctuation, thrust break down, cavitation erosion).

3. Review the current CFD methods for cavitation extent and hull pressure fluctuation prediction and especially on the use of a dummy model (defined by using CFD calculation) on propellers / pods / other types. Liaise with the Specialist Committee on CFD/EFD Combined methods. Provide recommendation for a new guideline on how to proceed for the dummy model definition.

4. Review the currently available CFD benchmark data, including the on-going projects, such as JORES, and investigate the feasibility to establish an ITTC benchmark database.

5. Review new measurement techniques used for cavitation model testing and full-scale trials (optical measurement for blade cavity extent, fluctuating forces on blades…).

6. Organize the proposed round-robin test case as recommended in the 29th Noise committee.

7. Monitor and investigate specific aspects of model-scale noise measurements including reverberation, tip vortex scaling, water quality and the effect on uncertainty.

8. Review any open literature dealing with the respective contributions of the hull vibrations and of the propeller in the ship radiated noise at full scale (frequency line and broad band spectrum) and investigate ways of assessing those contributions

9. Continue monitoring progress on shipping noise measurement procedures for shallow water and regulations as developed by ISO, classification societies and regulatory agencies.

10. Continue monitoring progress on ship noise prediction by computational methods with emphasis on the prediction of cavitation noise using CFD methods and methods such as data driven models and machine learning techniques, and noise propagation modelling, especially for shallow waters

2. STATE OF THE ART

The assessment of underwater radiated noise (URN) and/or cavitation phenomena from vessels now plays a central role in ship design. Cavitation consequences (noise, erosion, thrust break-down, etc.) are well-known but still difficult to predict at the full scale accurately. Many different phenomena have to be taken into account in such studies (hydrodynamics, acoustics, vibrations, mass transfer, water quality, etc.).

In section 3, this report reviews the procedures and guidelines that have been updated with a focus on the main changes. Section 4 is dedicated to the extensive review of the literature and recent studies dealing with cavitation (§4.1), noise (§4.2) and vibrations (§4.3). Numerical and experimental aspects are presented.

IMO background

The IMO (International Organization for Standardization) started to pay attention to the adverse effects of ship underwater noise on marine life in 2005. In 2007, the United States proposed to study the impact of shipping noise on marine life at MEPC 57 (Marine Environment Protection Committee). In 2014, IMO issued the first edition of "Guidelines for The Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life" (MEPC.1/Circ 883). In 2019, Australia and other countries proposed to review the first edition of the guidelines at MEPC 75, their research survey shows that there is no indication that these guidelines have had any impact. In June 2021, IMO agreed to further study the underwater noise from ships, and MEPC 76 agreed to review and update the first edition of the guidelines. The SDC 8 (Sub-Committee on Ship Design and Construction) Underwater Noise Communication Group submitted a guideline to MEPC 80 for review, which was approved in July 2023 as MEPC.1/Circ 906. The purpose of these Guidelines is to provide an overview of approaches applicable to designers, shipbuilders and ship operators to reduce the URN of any given ship; and assist relevant stakeholders in establishing mechanisms and programmes through which noise reduction efforts can be realized. Meanwhile the MEPC.1/Circ 906 is approved to provide additional information and guidance to operators transiting Inuit Nunaat and the Arctic.

SDC approved convening an Expert Workshop on Underwater Radiated Noise and Ship Energy Efficiency, this encouraged submission of best practices on implementation as guidance prior to the release of MEPC 85. Discussion included the flow chart of the noise management plan, the priority of noise reduction measures, the setting of underwater noise target values and the classification of underwater noise from ships. Currently, the impact of ship underwater noise on marine ecosystems remains an unresolved issue. More research is needed in the future to understand the impact of ship underwater noise on marine ecosystems and to develop more effective mitigation measures.

The ITTC Specialist Committee on Noise contributed by submitting the following document to IMO during the development of their circulars; ITTC 2023, "Review of full-scale ship noise measurement and estimation techniques".

3. PROCEDURES

All the procedures and guidelines have been updated. The main task has been making all the documents consistent with each other. Therefore, a global document, based on the procedure 7.5-02-03-03.2, has been extensively updated to give a common base for all the other procedures and guidelines. It has been renamed "Visual description and measurement of cavitation events." It proposes global features and a common description of the cavitation events that could be observed in many configurations. Specific aspects of a given configuration have been maintained in the other documents only if applicable for the procedure.

3.1 Model-scale cavitation test

The document 7.5-02-03-03.1 has been revised to ensure consistency with all other procedures and guidelines in terms of definitions and references.

3.2 Visual description and measurement of cavitation events

The procedure 7.5-02-03-03.2 includes the information that are common to all the other procedures or guidelines. The description of cavitation has been extended with super-cavitation. A section on cavitation observations on podded propulsors and a section on measurements of cavitation events have been added.

3.3 Cavitation induced pressure fluctuations: model scale experiments

The document 7.5-02-03-03.3 has been revised to ensure consistency with all other procedures and guidelines in terms of definitions and references. The discussion about the wake field has been updated.

3.4 Cavitation-induced pressure fluctuations: numerical prediction methods

The document 7.5-02-03-03.4 has been revised with different numerical approaches. Also, recent references have been added to illustrate the results obtained by the different methods.

3.5 Model experiments including numerical simulation guidance for propeller and rudder cavitation erosion

The document 7.5-02-03-03.5 combines the two previous rudder and propeller erosion procedures[1]. The numerical simulation has been extended to reflect current practice.

3.6 Podded propulsor model scale cavitation test

The document 7.5-02-03-03.6 has been revised to ensure consistency with all other procedures and guidelines in terms of definitions and references.

3.7 Modelling the behaviour of cavitation in waterjets

The procedure 7.5-02-03-03.8 has been reorganized and updated with the addition of more recent references, including experiments and simulations with the ONR AxWJ-2 axial flow waterjet pump geometry.

3.8 Model-scale propeller cavitation noise measurements.

The document 7.5-02-03-03.9 maintains most of the content of the previous guideline[2], except for some minor corrections and/or modifications to ensure consistency with other procedures and guidelines.

3.9 Underwater noise from ships, full scale measurements

The document 7.5-04-04-01 has been updated with a focus on special requirements for test sites and hydrophone deployment. The section on shallow water measurements includes propagation loss assessing methods for ship radiated noise source level estimation.

4. CAVITATION AND NOISE ACTIVITIES

4.1 Cavitation

4.1.1 Experimental model testing

A large number of recent publications on model scale cavitation tests deal with noise measurements which are treated in Section 4.2.1 of this report. The developments in the field of optical measurements and laser techniques are mainly dealt with in Section 4.1.2.

Measuring the flow field of the propeller is important to understanding the source of pressure fluctuations and noise to improve numerical modelling. Guangnian *et al*. (2020) measured the flow field near the blade tip using the 2D-PIV technique. They monitor the process of generation and shedding of the propeller tip vortex in real time and analyze the dynamic structure of the tip vortex.

Yilmaz *et al*. (2020) present further systematic measurements conducted in the Shanghai Jiao Tong University (SJTU) cavitation tunnel with “The Princess Royal” benchmark propeller in open water conditions, including cavitation observations with tests for tip vortex cavitation inception and desinence. The study also includes a computational fluid dynamics (CFD) investigation to discuss the results of the experiments, concentrating on comparing tip vortex cavitation.

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[1] The two previous documents were the procedure 7.5-02-03-03.5 entitled Cavitation Induced Erosion on Propellers, Rudders and Appendages Model Scale Experiments and the procedure 7.5-02-03-03.7 entitled Prediction of Cavitation Erosion Damage for Unconventional Rudders or Rudders Behind Highly-Loaded Propellers

[2] Note that the previous, now obsolete, guideline was numbered as 7.5-02-01-5.

Mingtai *et al*. (2022) use acoustics for determination of cavitation inception. Classic noise spectrum analysis is compared to the continuous wavelet transform and DEMON spectrum analysis.

Chao *et al*. (2022) present a case study on waterjet system cavitation and pressure fluctuations. Wavelet Packet Transform and Fractal Dimension Exponent to analyze the features of cavitation pressure pulsation signals. The methods can be used for detection of cavitation inception and performance loss due to cavitation.

Wu *et al* (2022) study short-term pressure pulses caused by propeller-hull vortex (PHV). This is a common phenomenon when a highly loaded propeller works in an ice-blocked stern wake field. Since the fluctuating pressure signal is not repeated in a periodic manner, it is necessary to analyze the frequency characteristics in different time of the fluctuating pressure signal. The authors use short-term Fourier transform (STFT) to analyze the time-frequency characteristics of the fluctuating pressure induced by propeller cavitation in the ice-breaking condition.

Krasilnikov *et al*. (2022) address the challenge of propeller noise predictions in a paper with rich data comparisons EFD/CFD.

Aktas *et al*. (2020) study different paint types and application methods for the soft paint technique for cavitation erosion in model scale. This is an interesting comparison since most facilities paint composition is kept secret.

Abbasi *et al*. (2022) present an experimental case study on blade root cavitation erosion where they use the soft paint technique and high-speed video. This research addresses two main aims: broadening the knowledge about hydrodynamic mechanisms responsible for cavitation erosion occurring at the blade root, and assessing a simple experimental procedure able to measure the erosion risk associated with cavitation to create a correlation with full scale data.

Özsayan *et al*. (2022) compare numerical methods with model scale data using the soft paint method. Erosion formation on the propeller was estimated using the Erosive Power Method (EPM).

Dong *et al*. (2022) study cavitation impact load and pitting in brass using FEM. They compare experimental tests using magnetostrictive ultrasonic vibration cavitation erosion apparatus (ASTM G32). The load distribution corresponding to the deformation is deduced by using the finite element method (FEM). The predicted cavitation impact load is correlated with the parameters describing the cavitation flow erosiveness of the hydrofoil. On this basis, the cavitation depth distribution on the surface of a NACA0015 hydrofoil is preliminarily predicted.

Usta *et al*. (2023) study erosion in marine propeller materials using the cavitating jet technique (ASTM G134).

Ju and Choi (2022) present a systematic study on pitting/material loss in full-scale for small ship propellers. They quantify the damage by weighting and liquid penetrant testing (PT) was used for the non-destructive examination of propeller erosion damage. An image processing technique is applied to the PT images to quantify the amount of pitting.

4.1.2 Measurement techniques

Experimental techniques have been developed to provide quantitative and accurate information about cavitation. Such information is crucial for the validation of cavitation computations, and for the understanding of propeller performance, as well as for addressing critical topics such as cavitation-induced vibrations and radiated noise. Visualization using optical devices has been at the centre of these approaches for decades as cavitation is an extremely visual phenomenon.

Still pictures using standard film photography or digital devices such as charge-coupled devices (CCDs), CMOS or other modern technologies, have been constant and reliable tools in cavitation testing, both at model and full scales. The methodology can provide high quality pictures that can be a useful tool to document the cavitation occurrence in classical propeller performance testing. Regarding the use of digital technologies, significant improvement can be attained by synchronizing the digital devices with the rotation of the propeller, with a once-per-revolution (OPR) pulse, and coupling it with a stroboscopic light. With the addition of a constant delay generator, it becomes possible to make pseudo-video recordings of the cavitation pattern at different angular positions, which can be useful to explore the range of variability of the cavitation extension during the rotation An implementation of this measurement approach is depicted in Figure 2.

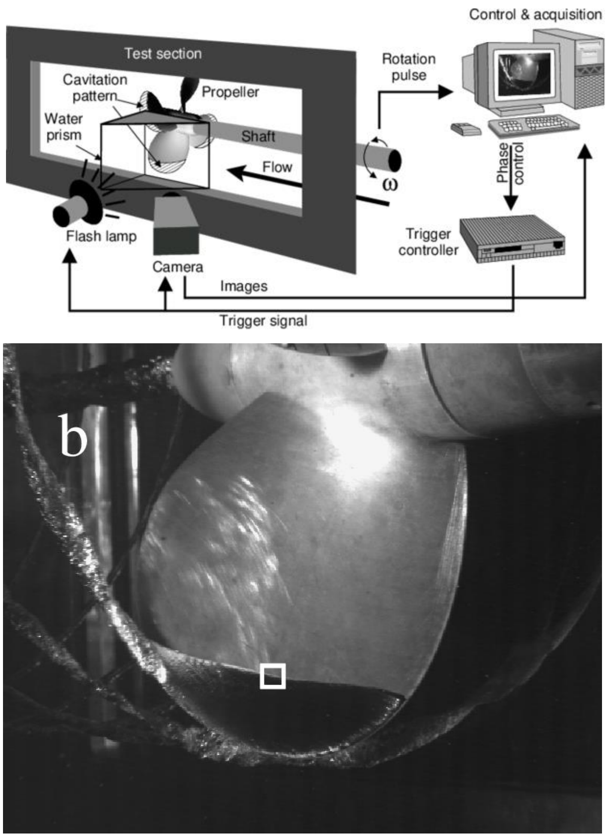


Figure 2: Setup for synchronized image recording using a digital camera and stroboscopic light (top); sample image (Pereira *et al*, 2004)

Technical developments have made possible by the time-resolved recording of cavitation using high-speed cameras, thus allowing the visual analysis of unsteady cavitation typical of a propeller operating in e.g. non-uniform flows deriving from off-design conditions. Guidelines for the operation of these techniques can be found in the ISO 22098:2020 document “Ships and marine technology - Full-scale test method for propeller cavitation observation and hull pressure measurement.”

However, still pictures, time-lapse or high-speed movies are not sufficiently informative for the purpose of computational validation, or for the purpose of correlating the visualizations with other quantities such as pressure fluctuations or noise data. Specifically, experimental methodologies and analysis tools are needed to retrieve quantitative information about the cavitation, either from visualization images or from other sources of information.

Lehman (1966) is, to our knowledge, the first to attempt the measurement of cavity volumes on a rotating propeller, using a laser-based technique. Ukon and Kurobe (1981), followed by Kurobe *et al* (1983) developed a similar approach to measure the cavity thickness at model and full scales. Pereira *et al* (1998) developed a four-camera tomographic system to capture cloud cavitation, enabling the definition of a size spectrum used to quantify the erosion potential. This complex technique is however not fully adequate for the measurement of attached cavities, such as leading-edge cavitation, since the three-dimensional reconstruction of the vapor volumes requires at least two sufficiently different viewing points to make measurements, with accuracy increasing with the number of views. Implementing computer vision algorithms based on the principles of triangulation and applied to stereo-vision, Savio *et al* (2009) used two cameras and laser beam projection to determine the cavitation bubble thickness over the blades as well as to spatially localize the cavitating tip vortex and measure its diameter. Shiraishi *et al* (2017,2022) implemented a variant of this approach based on a combination-line CCD camera measurement method to measure cavity shape and volume, see Figure 3. This measurement method also makes it possible to measure tip vortex cavitation, which has been difficult to determine in the past.

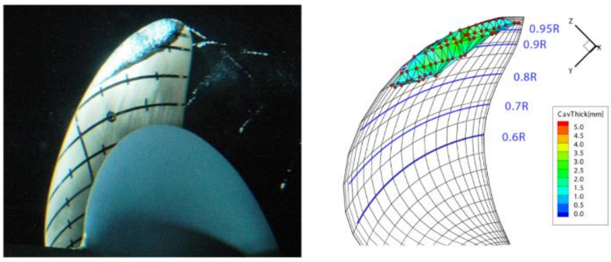


Figure 3: Combination-line technique to measure cavity volume and tip vortex size at model scale (Shiraishi *et al*, 2017, 2022)

The main disadvantage of these multiple-view systems is their requirement of significant optical access, since depth resolution is typically dependent on the separation between the viewing systems and on their distance to the object point, i.e. to the cavitation on the propeller blades. To remediate this problem, Felici *et al* (2013) proposed to use ultrasound pulsed echography (UPE) for the same purpose and applied it to leading-edge cavitation on a two-dimensional hydrofoil for validation, further comparing the results with the laser-line projection approach. The practical implementation of UPE is simple as it uses off-the-shelf instrumentation and is suitable for space-constrained configurations, or where optical access is limited or even non-existent. Processing of UPE data is also much faster since the operations measure the Doppler shift by a simple peak detection, and can therefore be performed in real-time. The main limitations of the UPE approach regard its large and distance-dependent measurement volume, the relatively low acquisition rate, and its sensitivity to background scatter noise such as the acoustic scattering from gas bubbles in the bulk of the fluid. In addition, and because it is based on a time-of-flight principle, its application to rotating machinery would require high-repetition rate pulse generation, which is limited by the speed of sound in water, as well as specific synchronization hardware.

Simple imaging of cavitation, done through still photography or synchronized digital recordings coupled with flash illumination, was exploited by Pereira *et al* (2004) to extract the area of the cavitation extension over the blades. Using image processing techniques based on established de-warping algorithms, and provided a dedicated but simple optical calibration, it was shown that accurate area measurements could be obtained. Inviscid flow boundary element method (BEM) computations of cavitation in uniform flow were validated through this data. A further step in this direction (Alves Pereira *et al*, 2016) was taken using one high-speed camera and continuous lighting. The same algorithmic approach was followed, allowing the possibility to explore and quantify unsteady cavitation, specifically the periodic variation of the cavity extension over the blade in a non-uniform wake presenting a typical skeg-like narrow pressure gradient. The mean and fluctuation of the cavity area could be determined, see Figure 4.

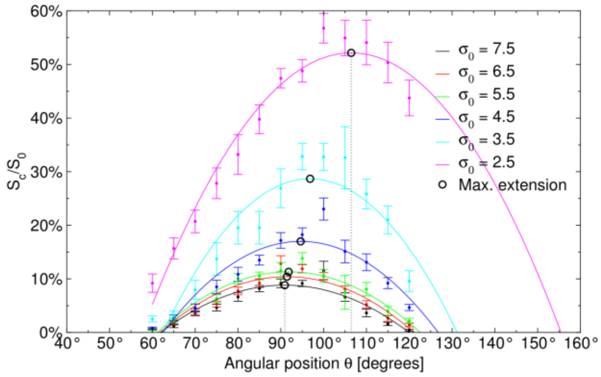


Figure 4: Cavity extension and corresponding root-mean-square fluctuations as a function of the propeller angle θ, for different cavitation numbers σ_0, with quadratic fit curves and indication of the location of the cavity maximum extension (circle markers) (Alves Pereira *et al*, 2016)

Cao *et al*. (2022) introduces an image-based experimental method for cavitation pattern analysis and pressure fluctuations. The method is based on the grey level frequency analysis of cavitation images from high-speed video.

Recent developments have demonstrated the application of Laser Doppler Velocimetry (LDV) to the simultaneous measurement of cavitation volume and of flow velocity on a rotating propeller, see Capone *et al* (2024). One major advantage of this approach is that the technique is insensitive to the light scattering typical of cavitation interfaces. The other unique advantage is its ability to access the inter-blade region, which is extremely difficult to probe using other velocimetry techniques such as Particle Image Velocimetry (PIV). The technique measures the three-component velocity field at a point of the fluid. The velocity field in a volume is reconstructed by traversing the microscale measurement point across this volume in an automated manner. The part of this volume where no velocity information is available represents either a solid boundary, such as the blade surface, or the cavitating domain. Therefore, it becomes possible to estimate the cavity volume from the missing LDV data. LDV has the major advantage that it can be built into an integrated system, compact, easy to setup and robust against vibrations. Feasibility has been demonstrated at model scale (Capone *et al* 2024), see Figure 5, however full-scale cavitation measurement has yet to be assessed.

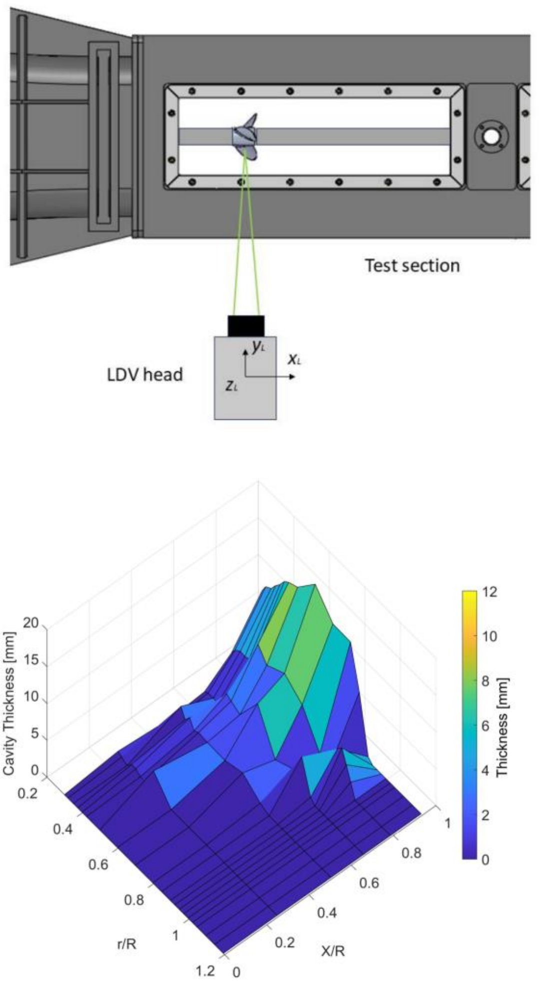


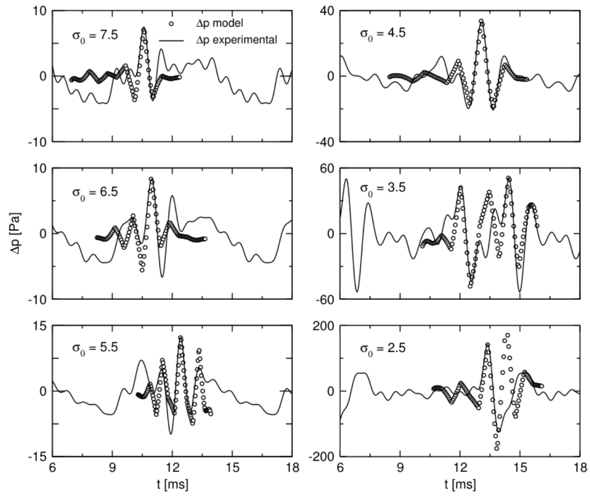
Figure 5: Cavity volume measurement using LDV: basic setup in tunnel (top); cavity shape (bottom) (Capone *et al*, 2024)

Recent works have considered the indirect measurement of cavitation from the radiated pressure field emitted by a cavity. On the assumption that a pulsating cavitation void behaves as a monopole source, the sound pressure radiated by this monopole is directly proportional to the acceleration of the pulsating cavity volume:

$$\Delta p \propto \frac{\partial^2 V_c}{\partial t^2}$$

The soundness of this principle has been demonstrated at model scale (Alves Pereira *et al*, 2016), showing that a measure of the cavity volume can provide accurate information about the radiated pressure field, see Figure 6.

Figure 6: Comparison between reduced-order Δp from measurements (-) and computed Δp from volume



acceleration (o) (Alves Pereira *et al*, 2016)

Recently, Fohring *et al* (2023) have proposed to reverse the principle by determining the cavity volume from the measured pressure fluctuations, and applied the approach to full-scale data obtained on a 3,600 TEU container vessel, see Figure 7. Fluctuations of the cavity volumes could be estimated as well.

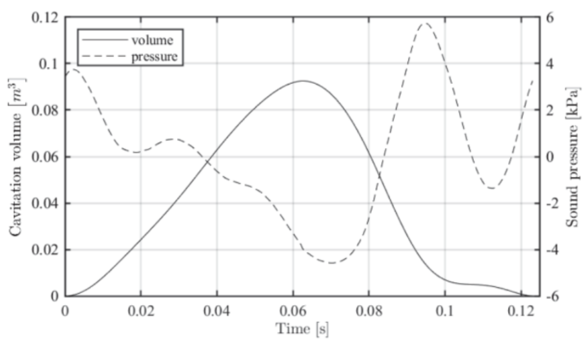


Figure 7: Representative sound pressure and cavitation volume of one blade passage (Fohring *et al*, 2023)

These authors point out that this reverse acoustic approach cannot "generally distinguish between cavitation types, so the calculated volume may well comprise a combination of sheet and tip vortex cavitation or other types." Moreover, the methodology is applicable if cavitation occurs on one single blade only.

Inukai (2019) implemented a technique called Multi-Layered Doppler Sonar (MLDS) to measure the flow velocity at the stern of a 14000 TEU container ship. The principle relies on the scattering of particles or bubbles in the flow field, thus creating a Doppler shift that is measurable and directly related to the particle/bubble velocity. The technique requires a limited amount of instrumentation and minimum intrusiveness into the ship structure:

Figure 8: MLDS equipped on 14,000TEU container ship (Left: the gate valve for the transducer of the MLDS at the bottom, Right: the transceiver of the MLDS and PC for analysis in the steering gear room) (Inukai 2019)

Although similar to the UPE approach used by Felici *et al* (2013), the authors did not explore the possibility of measuring the cavity volume.

Particle Image Velocimetry (PIV) is another advanced non-intrusive velocimetry technique that has been applied in different test cases of interest. Atsavapranee *et al* (2008) have been among the first to make full scale PIV measurements, by installing PIV cameras in underwater cases to investigate the viscous roll-damping around the bilge keel of a 88.6 m long navy ship. Kleinwächter *et al* (2014, 2015) improved the concept using onboard cameras, see Figure 9, and performed full scale velocity measurements on a 186.22 m long ConRo-ship. Hiroi *et al* (2019) used the same concept on a 63000 DWT bulk carrier. Birvalski *et al* (2023) devised a different implementation to measure the propeller inflow on a 50000 DWT tanker, with the PIV system being mounted externally and inside a rotating underwater case, adding some flexibility to the concept.

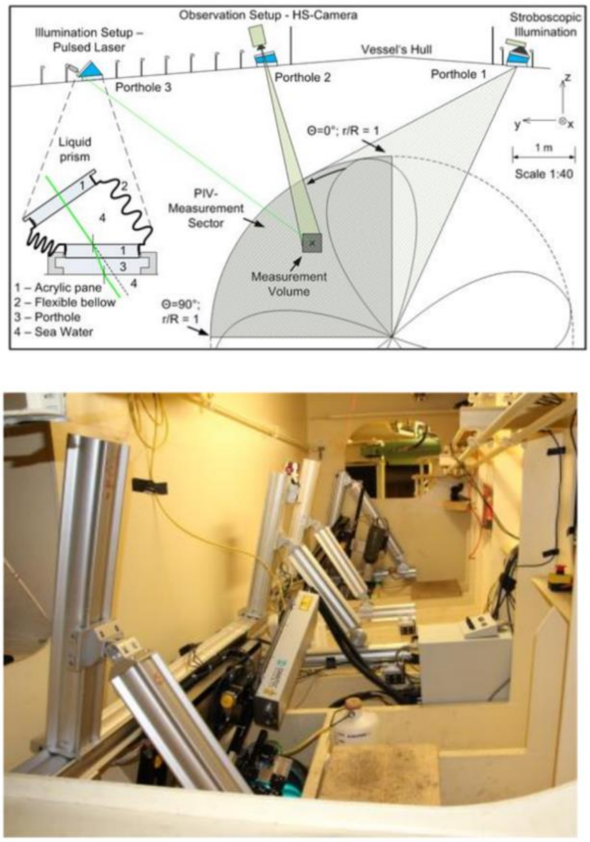


Figure 9: Schematic measurement setup (top) and actual setup (bottom) (Kleinwächter *et al* 2015)

Although PIV could potentially be used for cavitation volume measurement, as with LDV (Capone *et al*, 2024), the technique presents important challenges, such as limited access to the inter blade region, very limited flexibility due to critical alignment and space requirements, dangerous laser scattering on cavitation interfaces, etc.

Grasso *et al* (2019) developed a methodology to optically measure the hydro-elastic response of flexible propellers in non-uniform flow, and applied it at model scale in the cavitation tunnel and at full scale on a ship. The deformation of the propeller blades was measured optically with Digital Image Correlation (DIC) and two underwater cameras installed on the vessel's rudder, see Figure 10.

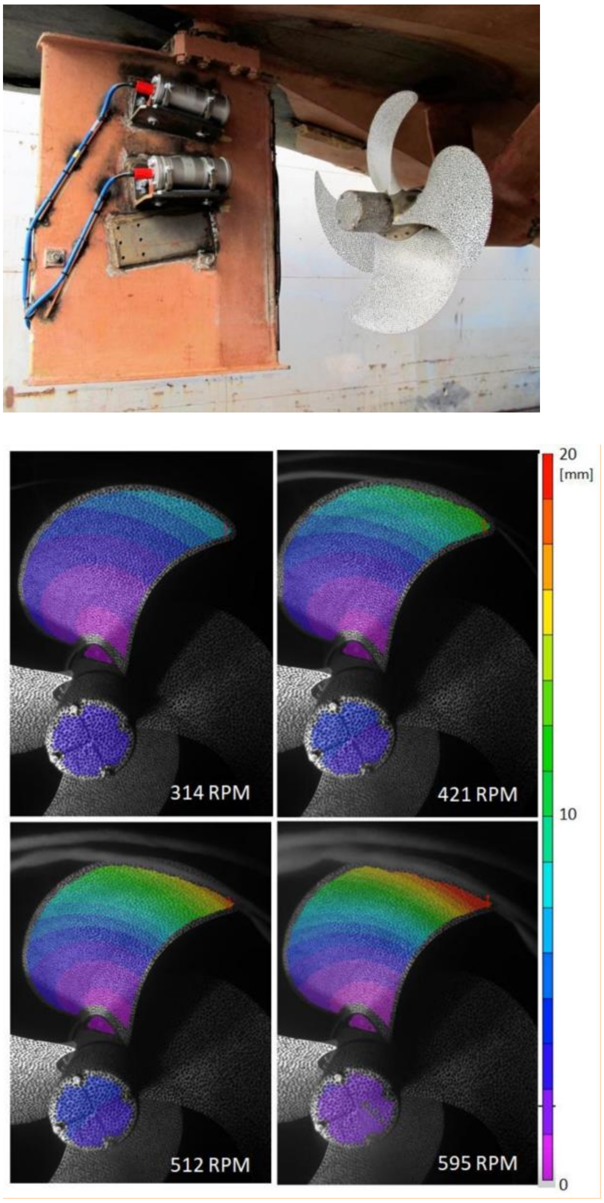


Figure 10: Full-scale setup (top) and deflection results (bottom) (Grasso *et al* 2019)

4.1.3 Numerical methods for cavitation induced pressure fluctuations

CFD has been widely utilized to simulate cavitation phenomena, from single cavitation bubble dynamics to macro scale behaviour like cavitation surge in hydraulic machinery. For marine propellers, nowadays CFD with cavitation modelling is adopted for predicting macro behaviour or appearance of cavitation and propeller performance, pressure fluctuation, erosion, and radiated noise.

Cavitation in marine propellers exists with wide spatial-and-time scale phenomena (i.e., from single bubble generation and collapse to extent or shedding of sheet or cloud cavitation on blade). Dealing with this multi-scale problem directly is difficult, especially in engineering applications. Therefore, most cavitation modelling for marine propellers is based on a mixture model, which treats cavitating flow as a mixture of water and vapour macroscopically, without directly modelling individual bubbles or interfaces between phases. This model is simplified in comparison with other types of methods like two-fluid models (simulate each phase's velocity and momentum independently) or Lagrangian models, but is widely used not only for marine propellers but also for other hydro-machines (for example, Nohmi *et al*. (2003)). This macroscopic modelling is also utilized for predicting cavitation erosion risk, although erosion basically comes from the collapsing of bubbles near the blade. For example, Hasuike *et al*. (2009) adopted indexes based on macro behaviour of cavitation and pressure from CFD to discuss erosion risk. Recently, Melissaris *et al*. (2018) applied an idea of potential power of macroscale propeller cavitation, related to time derivatives of pressure and vapour volume, to assess erosion risk on propellers based on URANS simulations. Similar methods were applied by Köksal *et al*. (2021) using URANS and DES results. The numerical results were compared to visual observations of cavitation paint tests. Figure 11 shows a visual comparison of a paint test result to a DES solution.

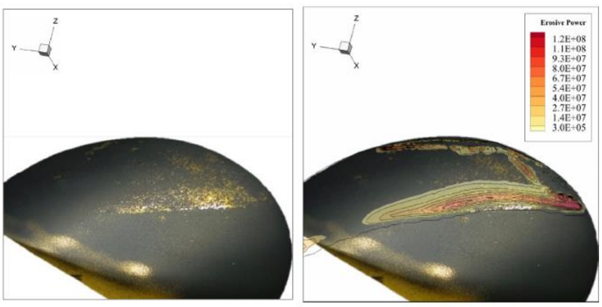


Figure 11: Visual comparison of paint test (left) and DES (right) (Köksal *et al*, 2021).

A hybrid approach with Eulerian mixture treatment along with Lagrangian bubble transportation has been studied to tackle the multi-scale problem. Tian *et al*. (2022) applied this approach to a cavitating hydrofoil. They adopted the Eulerian approach with VOF (Volume of Fluid) for large scale phenomena and the Lagrangian approach with a discrete bubble model for small scale phenomena simultaneously (Figure 12). This type of approach seems to have the potential to deal with erosion or noise with modelling individual bubble collapse.

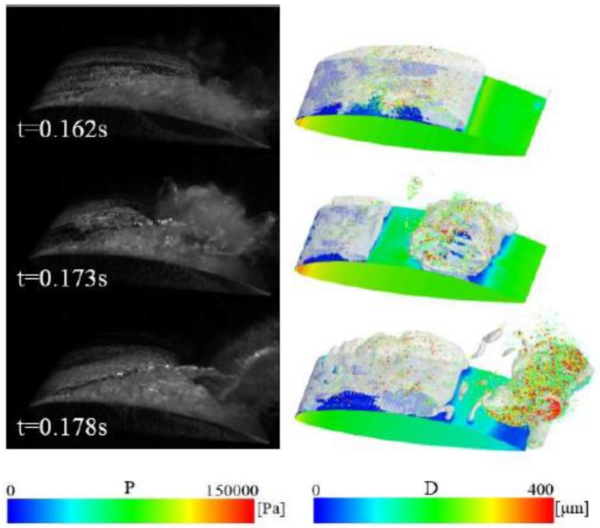


Figure 12: Cavitating flow around a hydrofoil (Tian *et al*. (2022))

To describe mass transfer between water and vapour (i.e., vaporization and condensation), several models have been developed and used. Most of these models basically apply the local pressure difference from vapor pressure to describe the mass transfer rate, but their theoretical origins and details are different. For example, Schnerr and Sauer (2001) derived their model from a simplified Rayleigh-Plesset equation, which describes single bubble dynamics. Other examples of relatively popular models can be found in, Singhal *et al*. (2002), Kunz *et al*. (2000), Zwart *et al*. (2004), etc. In another type of approach, Mike *et al*. (2022) tried to adopt a "Multi-process cavitation model" which is based on the moment method and solves detailed information of cavitation like number of bubbles, radius, surface, volume and mass. They applied this model to cavitating flow in a twisted hydrofoil and saw reasonable results in predicting cavitation shedding frequency.

Turbulence modelling is also an issue common to other CFD applications. Bensow (2011) studied the influence of the turbulence model on cavitation around a twisted hydrofoil. In his study, LES and DES could predict cavitation shedding behaviour and its frequency reasonably, but there is discrepancy in their lift. Also the Spalart-Almaras RANS model with eddy viscosity correction based on void fraction could predict the shedding, although a normal RANS model without the correction could not show shedding. Viitanen *et al*. (2020) studied the difference between model scale and full scale using DDES and RANS with/without a transition model. Two propellers, both in uniform flow, were simulated and there was little difference between the turbulence models. Geese *et al*. (2022) also studied using transition models with a propeller in uniform flow, and found that the model did not affect the overall behaviour of cavitation but there was some difference in radiated noise. Sezen *et al*. (2021) conducted a comparison between RANS and DES for a cavitating propeller in uniform flow. In this case, the difference in sheet cavitation was small, but the length of tip vortex cavitation agreed better in DES. Viitanen & Siikonen (2017) studied a model scale propeller in uniform flow using RANS, Reynolds stress and DES methods. While propeller performance and cavitation phenomena near the blades were similar between the models, wake flow and tip vortex cavitation extent were more dependent on the choice of the model. Additionally, they showed that using a compressive limiter for the convective terms in the void fraction equation resulted in an improved vortex cavitation prediction (Figure 13).

LES and DES approaches are generally better for simulating unsteady or unstable cavitation like cavitation shedding or vortex structures, but require greater computational resources (computational power and time) compared to the RANS approach. The appropriate approach should be chosen considering focusing phenomena simulations and allowable computational resources.

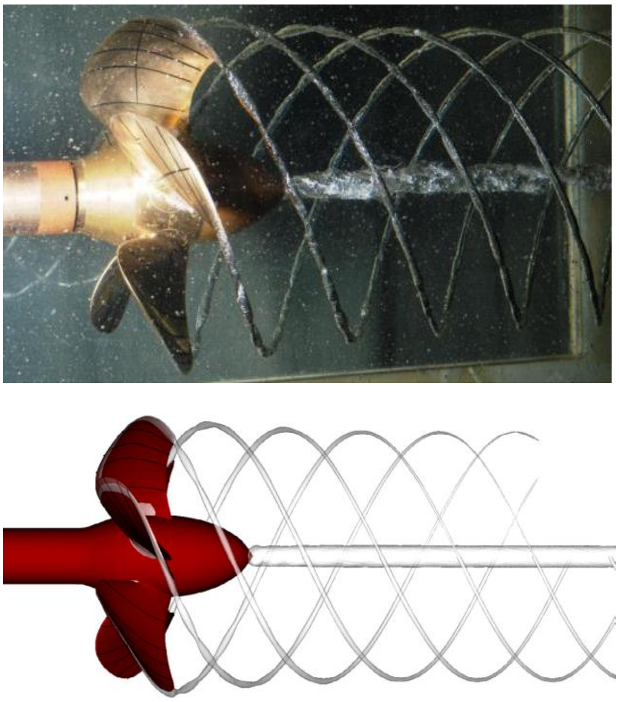


Figure 13: Comparison of computed cavitation extents with the different flux limiters (bottom) and experimental photograph (top) (Viitanen & Siikonen, 2017).

To reproduce the hull wake field, there are two types of methods similar to model tests. One is setting the hull shape in the calculation domain and calculating the wake development directly. The other is giving a prescribed wake distribution at the inlet as a velocity boundary condition. Many studies have been conducted with both methods (some of them are referenced later) but no significant difference in calculated cavitation extent or pressure fluctuation was suggested in this review. Also, there are some cases with an inclined shaft arrangement without wake, to realize the same condition as the corresponding model test.

Early application of CFD to cavitating propellers can be found in Watanabe *et al.* (2003) with good agreement between CFD and model tests of sheet cavitation in a uniform flow. Subsequently the application was expanded to predicting unsteady cavitation in a wake and its pressure fluctuation. Sato *et al.* (2009) studied CFD's applicability in ten different propellers for various merchant ships and found that the appearance of sheet cavitation and its difference between propellers were well predicted. The tendency of the 1st order component of pressure fluctuation above the propeller centre was relatively well predicted. The 2nd order components were underestimated, with rough time stepping being indicated as one of the reasons for the variation. Hasuike *et al.* (2015) conducted calculations for twenty propellers and obtained 1st order comparisons, as shown in Figure 14. In addition, they attempted to calculate 2nd order components from the 2nd order time derivative of the cavity volume and this resulted in decreasing the discrepancy between CFD and model tests.

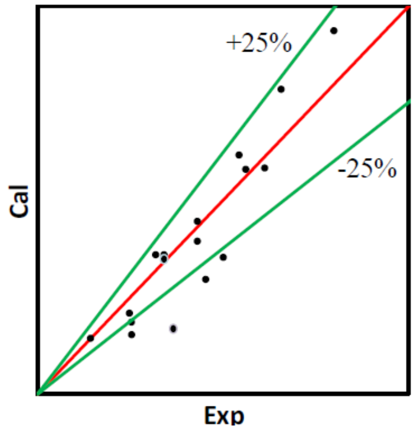


Figure 14: Comparison of 1s order component of pressure fluctuations. (Hasuike *et al*. (2015)

Paik *et al*. (2013) conducted simulation for two propellers with the hull present and compared the cavitation appearance and pressure fluctuation distribution on the hull with model tests. Good agreement of the two propellers 1st order components was found when comparing various locations on hull, as shown in Figure 15. On the other hand, 2nd order components had relatively large discrepancies. Similar results can be seen in works by Park *et al*. (2018) (Figure 16), Deng *et al*. (2022), Viitanen *et al*. (2022) and Zhen *et al*. (2022).

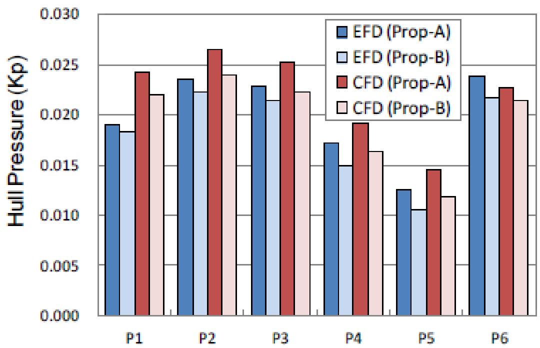


Figure 15: Comparison of pressure fluctuations in 1st order. (Paik *et al*. (2013))

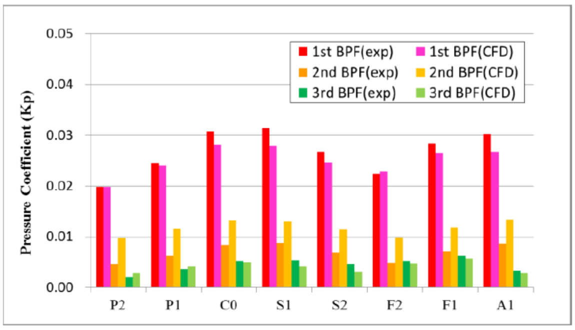


Figure 16: Comparison of pressure fluctuations (Park *et al*. (2018))

Fujiyama (2015) adopted adaptive mesh refinement[3] (AMR) for tip vortex cavitation and had good results in presenting cavitation extent. In addition, a discrete wavelet analysis was applied to the cavitation surface pressure and indicated cavitation behaviour around the trailing edge of the tip has a relatively strong relation to 2nd order pressure fluctuations (Figure 17).

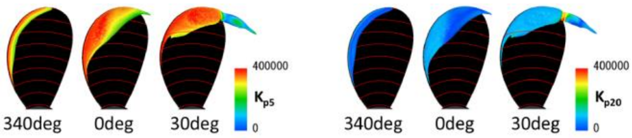


Figure 17: Contribution of cavitation to pressure fluctuation. (Left : 1st order, Right : 2nd order) (Fujiyama (2015)

AMR technique was studied by Yilmaz *et al*. (2019) and resulted in a good prediction of detailed tip vortex cavitation appearance, for a propeller in uniform flow (Figure 18).

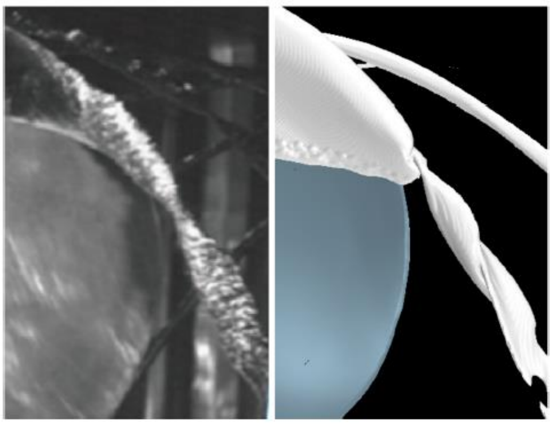


Figure 18: Comparison of tip vortex cavitation roll-up (Yilmaz *et al*. (2019))

Regarding the influence of turbulence modelling, Chaosheng (2017) applied an eddy viscosity correction to RANS (SST k-ω). This approach is similar to Bensow (2011) which showed a positive effect on cavitation shedding on a hydrofoil, but in this case the influence on pressure fluctuation was small (Figure 19).

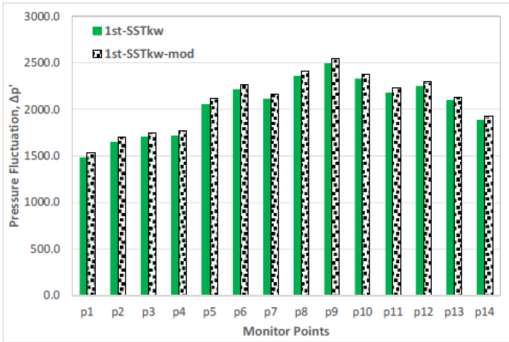


Figure 19: Comparison of pressure fluctuation with viscosity correction (Chaosheng (2017))

Kimmerl *et al*. (2022) conducted comparisons between RANS, LES and LES with AMR for tip vortex cavitation. In cavitation appearance, the difference between RANS and LES was small but improvement in vortex cavitation representation was shown with AMR (Figure 20, here "QRef" means "with AMR"). Regarding pressure fluctuation, LES showed good agreement with model tests in the 1st order component, but the improvement was not clear in higher order components (Figure 21).

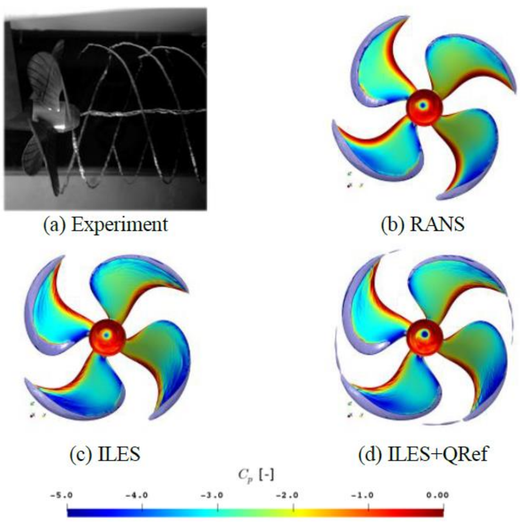


Figure 20: Cavitation appearance in several turbulence modelling (Kimmerl *et al*. (2022))

[3] Adaptive mesh refinement is local mesh refinemnet by cell size adjustment based on calculated flow characteristics like pressure or velocity.

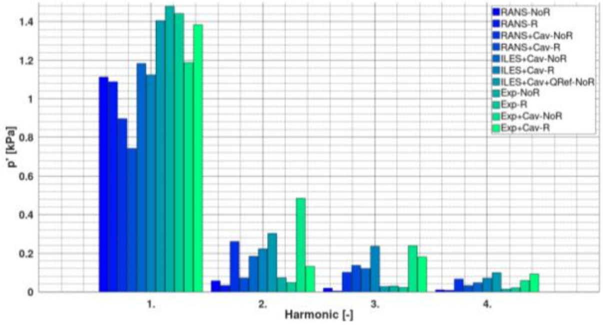


Figure 21: Comparison of pressure fluctuations (Kimmerl *et al*. (2022))

From these studies, the current state of CFD predictions for cavitation extent and pressure fluctuations is summarized below.

- The extent of sheet cavitation on a propeller operating in a wake can be predicted well. Sometimes the tip vortex cavitation appearance is also well predicted with an AMR technique or high-resolution mesh.

- Regarding pressure fluctuations, the 1st blade passing frequency component is predicted reasonably. Although, it is still difficult to predict the 2nd order and higher components.

To obtain reasonable results, careful consideration when utilizing CFD is necessary. Further discussion can be found in ITTC Recommended Procedures and Guidelines 7.5-02-03-03.4 "Procedure for Cavitation-Induced Pressure Fluctuations: Numerical Prediction Methods."

As the pressure fluctuation is related not solely to cavitation extent, but also to the 2nd derivative of cavitation volume variation, much higher accuracy is required. To improve the accuracy of predicting higher harmonics, improvement in predicting tip vortex cavitation or other complicated phenomena like cloud cavitation or bursting might be needed. At the same time, the importance of validation or uncertainty analysis in model tests, especially for higher order pressure fluctuations should be noted.

4.1.4 Dummy models

A dummy model is used to provide a representative hull wake field for testing propellers in a cavitation test. The shape of the dummy model is usually different from a geometrically similar full scale ship (e.g. Figures 22 and 23), but the method for designing or evaluating a dummy model has not been clarified and generalized as a recommended procedure or guideline.

Figure 22: An example of dummy model and its setting in cavitation tunnel (in INM)

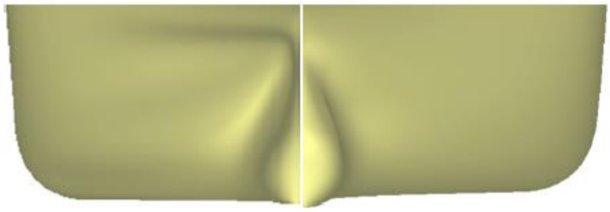


Figure 23: An example of designed dummy model (Left: designed dummy model, Right: original geosim hull) (Schiling *et al*. (2011))

To understand the facilities' experiences with dummy models, a questionnaire was distributed to twenty-seven organizations using cavitation tunnels, sixteen organizations kindly provided their answers.

An overview of the results is provided in the following sections.

4.1.4.1. Fundamental information of facilities and test objectives.

Nine out of the 16 facilities use dummy models, and many of them (7 out of 9, hereafter simply "7/9") are using dummy models as established practice.

Six facilities use dummy models although their test sections are relatively large, i.e. their width and height are over 1.0m, and might be able to use a fully geometrically similar hull model.

Typical model propeller diameters used are around 250mm, similar to common cavitation tests without dummy models.

Regarding water quality control, upstream microbubble injection and/or adjustment of gas content are widely adopted similar to common cavitation tests. Using an electrolysis device on the dummy model is not common practice (3/9).

The objective of the cavitation test with a dummy model is similar to standard cavitation tests: cavitation observation, measurement of pressure fluctuation, URN, investigation of inception, erosion, etc.

4.1.4.2. Target wake and evaluation of simulated wake

Many of facilities (7/9) using dummy models attempt to simulate an estimated full scale wake, and approximately half of facilities (5/9) intend to simulate full 3D velocity components including radial and tangential at the propeller disk plane. On the other hand, turbulence intensity and pressure distribution are rarely (1/9) part of the simulation.

There are two methods for evaluation, i.e. by experimental measurement in tunnel, or/and numerical prediction, but experimental measurement is dominant (7/9). Almost half of facilities (4/9) have some clear criteria for wake simulation. The criteria between facilities vary widely (e.g. less than 15% use a 3-dimensional velocity, less than 5% in velocity amplitude difference) to more qualitative ones like “width of the low-speed areas,” “phase angle of wake field” and “visual comparison of curves”. It appears difficult to find common criteria for this part of the survey.

4.1.4.3.Details of dummy models and their design

The dummy model shape for (7/9) facilities models the aft hull section as geometrically similar with full scale. When deviating from a geometrically similar aft end hull shape, some points like tip clearance, configuration of shaft bracket and rudder are maintained to directly scale with full scale. Also the stern tube shape is sometimes modified to accommodate. In some cases, where the aft hull shape is maintained with full scale, there are cases where the hull’s beam must be adjusted to fit the tunnel. Also, many facilities (7/9) adopt appendages, e.g. rudder, shaft, shaft brackets, ESD such as pre-swirl fins, thruster housing, ducts, bilge keel, sonar dome and stabilizer.

There are not many descriptions or comments on fore hull shape, but one facility indicated that fore shape also affects the wake meaning the bow geometry should be geometrically similar to full scale.

In addition to dummy models, some facilities (2/9) adopt an additive wire mesh to obtain the required wake. One facility adopts flow liners on the wall of the cavitation tunnel, to shrink the wake distribution.

Criteria on blockage against the tunnel section varies from 10% to 30% depending on the facility. One participant commented that the effect is taken into account in CFD simulations for designing their model.

In designing the dummy model, both experimental measurement and numerical simulation are commonly used, but which type is adopted is dependent on the facility. All numerical simulation methods used are RANS type CFD, and most of them (5/6) are commercial codes. Using RANS, some facilities conduct unsteady simulations, but the results are utilized as time averaged mean flow information. No facility considers unsteadiness or unstableness directly. Regarding the components predicted or evaluated by numerical simulation, most facilities (5/6) consider not only axial velocity distribution but also tangential or/and radial velocity distribution. Checking for the occurrence of unintended flow separation or other flow modes is also in the scope (3/6). Some facilities also consider turbulent intensity or pressure distribution. The typical accuracy of these CFD simulations for dummy models is not clarified in this survey, but one facility commented that the outer area is usually well predicted but not always the inner radius, especially if there is flow separation.

Using these numerical simulations, one facility indicated that the dummy model hull shape is parametrized and iteratively adjusted to obtain the target wake, but generally no special optimization system is utilized.

4.1.4.4.Problems utilizing the dummy model

A main concern raised when using a dummy model is the difficulty of simulating the tangential and radial components of the wake. One facility does not feel this is a problem but several other facilities consider it difficult to achieve sufficient results and it can be very time consuming. This indicates that the design method for dummy models is not well established between facilities and requires further research and discussion to determine the key components that affect results.

Other problems indicated in this survey are more specific to each facility's situations. For example, time and cost consuming risk comes from their model manufacturing. Also, one facility expects cost reduction by using dummy models with a common fore body with modifications in the aft hull section only, but this assumes the fore body shape does not affect the wake into the prop plane.

4.1.4.5.Recommendation for a new guideline

Currently it is difficult to provide a procedure for defining the shape of dummy models, as the survey highlights many variations between facilities. Ideally the new guideline will provide fundamental ideas and examples of the shape and its evaluation.

The contents might include points like following.

- The typical shape of dummy models is a shortened hull where the aft part is geometrically similar to the full scale ship. The aft hull sometimes requires modifications due to limitations from model test equipment like the dynamometer.
- The fore hull shape can affect the wake into the propeller plane, so the shape of fore hull should be discussed carefully.
- Appendages like the shaft bracket, rudder etc. should be adopted.
- In addition to the hull, wire-mesh may be adopted to improve the wake quality. Also, a liner on the tunnel walls may be used to shrink the hull's wake.
- The resulting design should be evaluated with measurement or numerical prediction. In addition to axial wake, tangential and radial components might be in scope. Other flow characteristics like static pressure and turbulence intensity could also be discussed.
- The design might be run iteratively until the target wake is obtained.
- There is no separate criteria for wake simulation with a dummy model, and it will follow the discussion of wake simulation without a dummy model. (see ITTC Recommended Procedures and Guide-lines 7.5-02-03-03.1 "Procedure for Model-Scale Cavitation Test")
- As numerical simulations, typically RANS-type CFD are utilized for design and evaluation both steady and unsteady simulations (with its results time averaged) are used.

4.2 Noise

4.2.1 Model-scale measurement

Considering the recent growing importance of shipping noise, the specialist committee on hydrodynamic noise of the 27th, 28th and 29th ITTC had reviewed the model-scale noise measurement techniques in detail. ITTC guideline 7.5-02-03-03.9 on Model-Scale Propeller Cavitation Noise Measurements had also been updated to the latest reviewed knowledge.

The 30th ITTC specialist committee on cavitation and noise has reviewed the latest aspects of model-scale measurements more specifically on reverberation, tip vortex scaling, water quality, and its effect on uncertainty.

Facility reverberation has been widely recognized as a main cause of adverse effects on the reliable source level estimation of cavitating propellers at model-scale. The previous hydrodynamic noise committee mainly dealt with transfer function measurement techniques including the type of source signals (Tani *et al.*, 2019a,b; Park *et al.*, 2018b), transducer positions (Briançon *et al.*, 2013; Tani *et al.*, 2019b) and post-processing techniques to remove unrealistic humps and hollows in the measured transfer functions (Briançon *et al.*, 2013; Tani *et al.*, 2019b; Harrison & Harrison, 1995[4]). Demodulation techniques (Boucheron, 2019) to identify the mode characteristics inside the test sections were also examined in the previous report.

The acoustic characteristics of the test facility can also be studied by using numerical simulations. Way *et al.* (2021) proposed an adapted image source model to analyze reverberation effects in the towing tank at which noise measurements are performed. Figure 24 shows the lattice of image sources where their locations are controlled by vectors $\underline{u}$ and $\underline{l}$. This model includes volumetric absorption and the use of spherical wave reflection coefficients at the tank boundaries. The plane wave reflection coefficients only agree with spherical coefficients at near vertical incidence ($\leq 20°$) as shown in Figure 25. Three periodicities were identified in the frequency variation of the transfer function. The periodicities arise from Lloyd's mirror effect (1 in Figure 26), cut on of transverse modes between the sides of the tank and between the tank floor and free surface (2 in Figure 26), and interference between axial standing waves between the two end walls of the tank (3 in Figure 26).

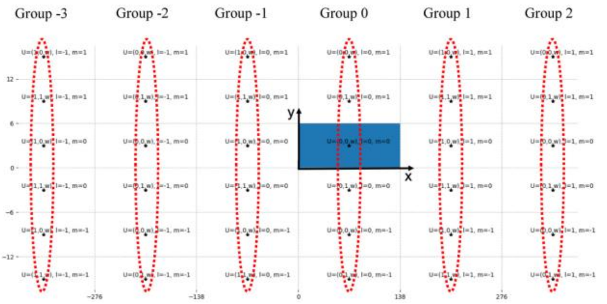


Figure 24: Lattice of image source in the x-y planes for a towing tank in which the position of each source is controlled by vectors $\underline{u}$ and $\underline{l}$ (Way *et al.*, 2021).

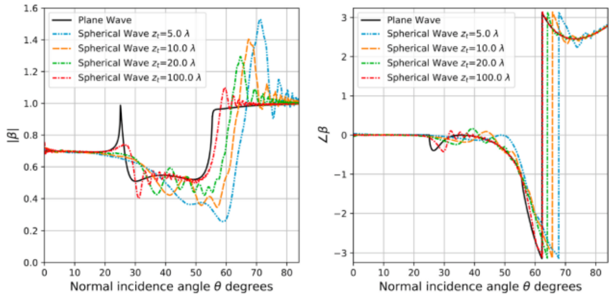


Figure 25: Examples of calculated reflection coefficients of plane and spherical waves (Way *et al.*, 2021).

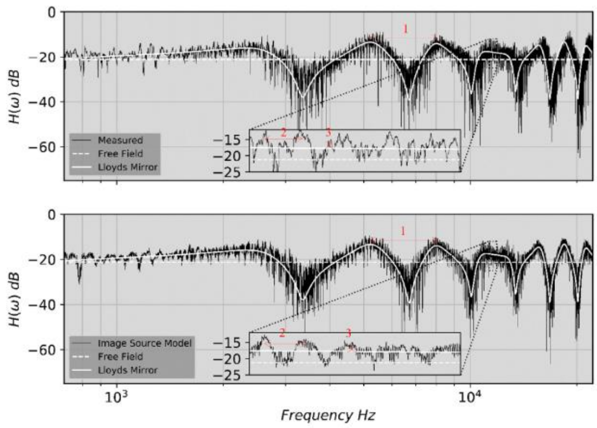


Figure 26: A comparison between measured (top) and simulated (bottom) transfer function (Way *et al.*, 2021). The analytical free field and Lloyd's mirror transfer functions are overlaid in white in the figure.

Boucheron (2023a) studied the scattering effects of the acoustic sources (typically spherical and cylindrical shaped projectors used for the transfer function measurements in the test section of a cavitation tunnel) using numerical simulations. The reflections from the surrounding walls are incorporated using the image method, the principles of which are similar to Figure 24. The scattered fields of

[4] The problem of smoothing is also well known in ocean acoustics

spherical and cylindrical projectors are simulated with spherical and cylindrical Bessel functions, respectively. Figure 27 shows a comparison between the simulated transfer functions with and without the scattering effects from a spherical shaped source. The values in the figure were picked from the points with maximum power. It was observed that the scattering effect can be neglected in the low frequency domain ($kR < 1$), however, it becomes significant as the frequency increases.

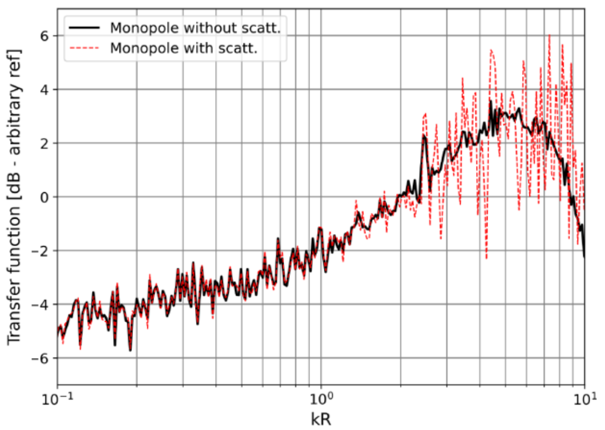


Figure 27: A comparison between simulated transfer functions with- and without the scattering effects of a spherical shaped acoustic source (Boucheron, 2023a).

It is noted that the transfer function measurement is not required if hydrophones or pressure sensors are used as onboard sensors (Foeth & Bosschers, 2016). Examples of estimating model-scale source strength with onboard sensors using array signal processing techniques[5] can be found in Foeth & Bosschers (2016) and Jeong *et al.* (2021). It is noted that those two references also dealt with full-scale measurements.

Foeth & Bosschers (2016) applied near-field beamforming to estimate source strength as well as source location. In order to validate the proposed method, they formed an array with flush-mounted pressure transducers embedded on the model ship and used a transducer fitted within the wake field measurement equipment as shown in Figure 28. Figure 29 presents a comparison between the nominal source strength and the estimates using array processing and two hydrophones[6]. It was observed that the estimates by the array processing shows good agreements with the nominal source levels except for the lower frequencies (≤ 5 kHz) due to the low transmitting power of the transducer. It was also noted that the relatively larger discrepancies above 15 kHz might come from reflections by the shaft, struts and traversing mechanism.

Figure 28: Model test setup used by Foeth & Bosschers (2016).

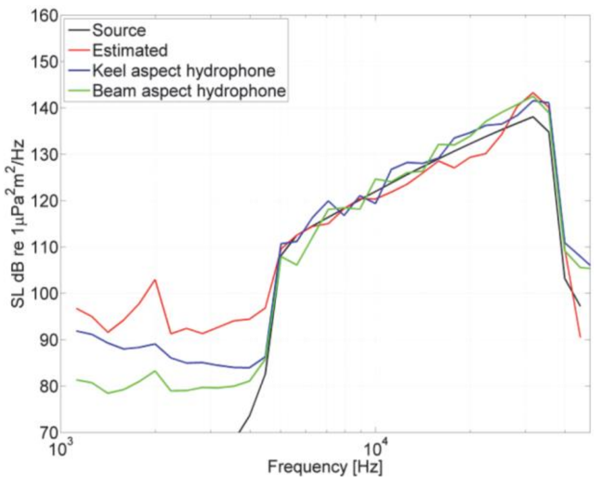


Figure 29: A comparison of estimated source levels to the nominal ones emitted by the source at the bottom of the propeller disc position (Foeth & Bosschers, 2016).

Jeong *et al.* (2021) also applied a simple beamforming method[7] to monitor the propeller

[5] The array signal processing technique was also used in wind tunnel aeroacoustic measurements (see Muller (Ed.), 2002).

[6] The source levels were obtained after applying corrections for the surface reflection (Lloyd's mirror effect) and for the distance between the source and the hydrophone to the sound pressure levels measured at an additional two hydrophones.

[7] The given method is similar with Foeth & Bosschers (2016) in principle.

noise in a model-scale measurement. They calculated an estimated source level at each source grid point using noise data measured at the hydrophone array in Figure 30 and the source strength was determined where the beamforming power was at its maximum. From the comparison between measured[8] and calculated source levels in Figure 31, it was confirmed that the proposed method can estimate the source level to a good degree.

Figure 30: Model test setup used by Jeong *et al*. (2021).

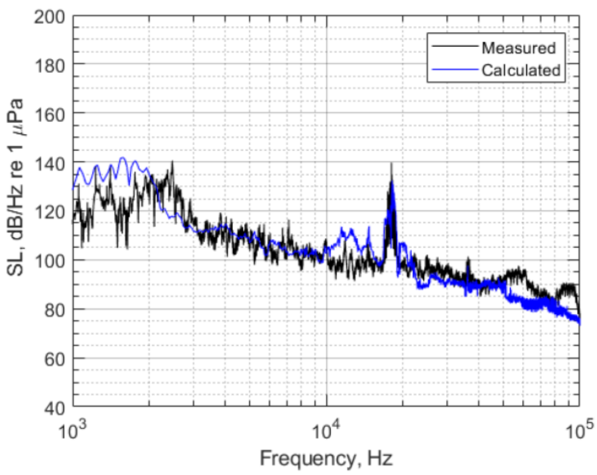


Figure 31: A comparison between measured and estimated source levels (Jeong *et al*., 2021).

The modal characteristics due to facility reverberation can be used for the localization of acoustic sources. Boucheron (2023b) proposed a demodulation technique for this purpose. It was shown through numerical simulations that the proposed method gives good performance especially for the lower frequency domain (between the two dashed lines in Figure 32) at which conventional array signal processing is not appropriate due to lower resolution.

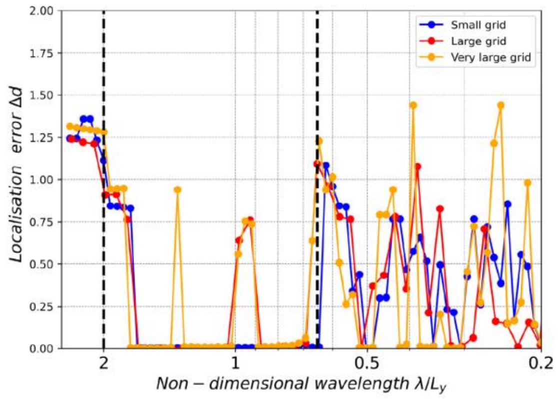


Figure 32: Localization accuracy against the non-dimensional wavelength for various grid size (Boucheron, 2023b).

After earlier publications to address the effect of Reynolds number on the noise of tip vortex cavitation (Strasberg, 1977; Baiter, 1989; Oshima, 1990, 1994; Blake, 2017), a few publications dealing with its scaling were reviewed in the report of the previous committee including Park & Seong (2017), Park *et al*. (2019, 2020), and Bosschers (2018, 2020).

Recently, Lee *et al*. (2024) proposed a scaling technique for tip vortex cavitation noise and presented scaling results from model-scale experiments. In this study, a relationship between tip vortex cavity size and cavitation model, which provides information on the equivalent cavitation number for the model test condition to ensure the same non-dimensionalized radius of the TVC as the full-scale one, was derived from the empirical vortex model proposed by Proctor *et al*. (2010). A new scaling exponent, k_{ce}, was introduced in this study based on the assumption that the exponent relating the cavitation number (σ) and Reynolds number (Re) of the model-scale (m) and the full-scale (s) varies according to cavitation growth:

$$\frac{f_s}{f_m} = \frac{n_s}{n_m}\left(\frac{Re_s}{Re_m}\right)^{0.5k_{ce}} \quad (1)$$

$$\Delta L_s = 10log_{10}\left[\left(\frac{r_m}{r_s}\right)^2\left(\frac{n_s D_s}{n_m D_m}\right)^3\left(\frac{D_s}{D_m}\right)^3\left(\frac{Re_s}{Re_m}\right)^{1.5k_{ce}}\right] \quad (2)$$

[8] The source level was measured using the transfer function correction.

$$k_{ce} = \frac{log_{10}\left(\frac{\sigma_s/\sigma_{i,s}}{\sigma_m/\sigma_{i,m}}\right) + log_{10}\left(\frac{\sigma_{i,s}}{\sigma_{i,m}}\right)}{log_{10}\left(\frac{Re_s}{Re_m}\right)} \quad (3)$$

Figure 33 shows an example of the scaling exponent, k_{ce}, derived from the equivalent cavitation number for two test conditions. Figure 34 presents a comparison between the full-scale measurements and the scaled source levels.

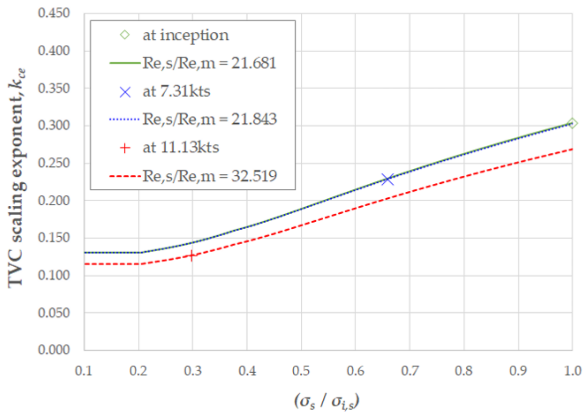


Figure 33: Scaling exponent, k_{ce}, derived from the equivalent cavitation number for two test conditions (Lee *et al*., 2024).

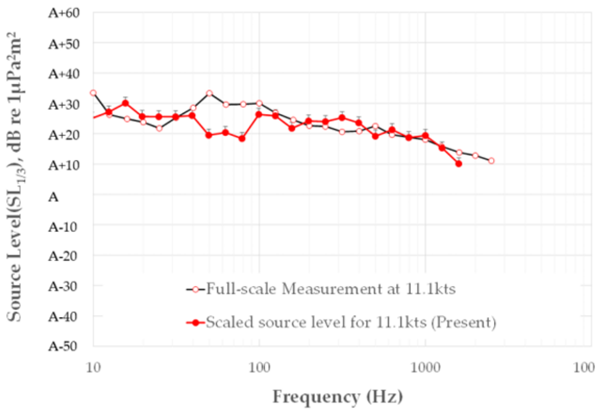


Figure 34: A comparison between the measured and the scaled source levels (Lee *et al*., 2024).

The effect of water quality, generally quantified by dissolved gas content, was reviewed in detail in the report of the previous hydrodynamic noise committee.

Khoo *et al*. (2021) recently investigated the effect of nucleation on tip vortex cavitation dynamics and noise. Two different nuclei populations, denoted as 'monodisperse' and polydisperse' in Figure 35, were used for measuring TVC inception of NACA0012 hydrofoil. Both the nuclei population and the ambient pressure were observed to affect the inception event rate significantly as shown in Figure 36. However, tip vortex kinematics and acoustics were influenced more by changes in local pressure (cavitation number) than by nuclei population and initial nucleus size (see Figure 37 for the effects on the acoustics). Khoo *et al*. (2021) noted the relative independence of nuclei size on cavity kinematics and acoustics might be due to the similarity of the bubble critical pressures in the 50-100 μm diameter range (see Figure 36 for the bubble diameter distribution).

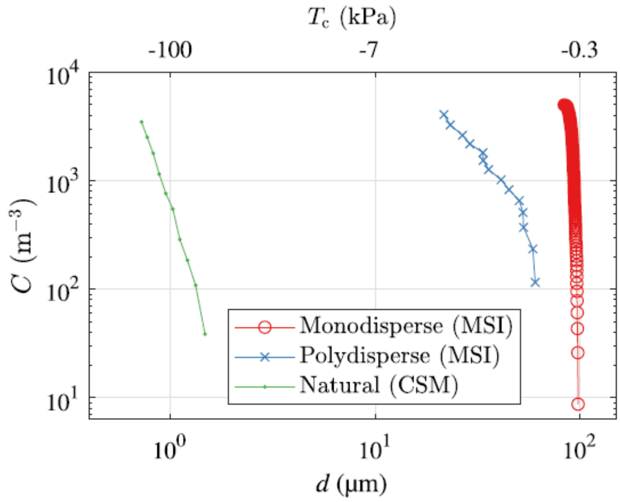


Figure 35: Injected nuclei populations used by Khoo *et al*. (2021).

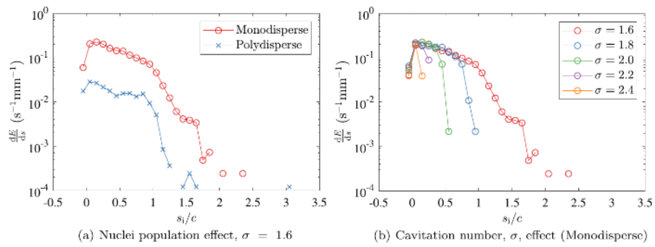


Figure 36: Effects of (a) nuclei population and (b) cavitation number on inception events rate density (Khoo *et al*. 2021).

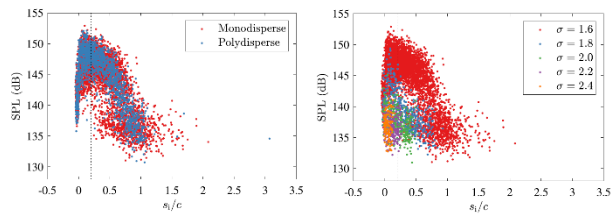


Figure 37: Effects of (left) nuclei population and (right) cavitation number on the sound pressure level (SPL) of inception events (Khoo *et al*. 2021).

4.2.2 Full-scale noise

A number of international committees and organizations have published or are drafting various standards to provide guidance on procedures and methodologies for measuring underwater noise from surface vessels, as shown in Figure 38.

Ship classifications societies, such as American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas Germanischer Lloyd (DNV), Lloyd's Register (LR), Registro Italiano Navale (RINA), China Classification Society (CCS), and Korean Register (KR), have published underwater radiated noise guidelines and notations. In addition, International Organization for Standardization (ISO) is developing international standards for measuring URN in deep water (ISO 17208-1:2016; ISO 17208-2:2019) and shallow water (ISO 17208-3/DIS:2024).

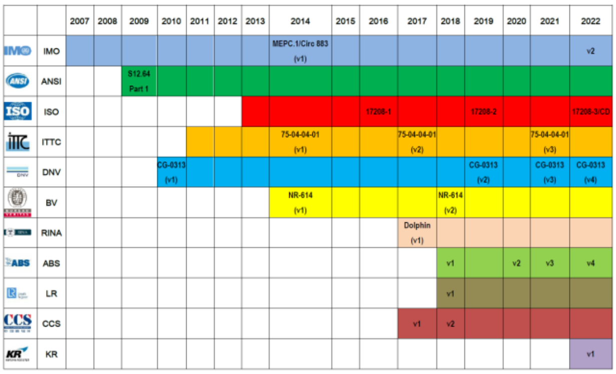


Figure 38: Guidelines and standards for URN measurement

However, these guidelines do not follow consistent methods for ship noise measurements, analysis, and reporting procedures. Therefore, certificates provided by different societies cannot be directly compared as shown in Figure 39, which hinders the determination of relative noise.

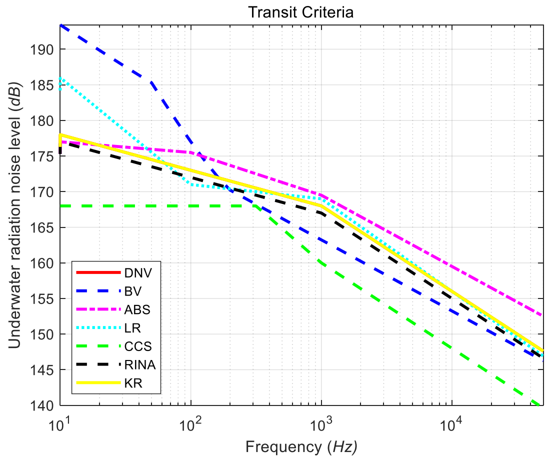


Figure 39: Limitation criteria for URN for Transit Condition of different classification societies. (Hannay *et al*, 2018)

To improve standard procedures for URN measurements in shallow water, the EU and Canada have launched several projects.

SATURN is an EU-funded project that develops URN standards and produces recommendations for effective underwater sound management. SATURN defines standards for terminology, methodology, tools and metrics for measuring, assessing and comparing the impacts of noise from shipping and boats. In the SATURN project, URN and background noise was collected for approximately 190 and 80 vessels respectively. Data was collected according to different procedures at water depths ranging from 50m to 200m using different instrumentation deployment strategies such as the drifting buoys, the moored surface buoys and two hydrophone seabed configurations. Figure 40 shows an example of reported differences of URN levels between ISO 17208-1 and other procedures.

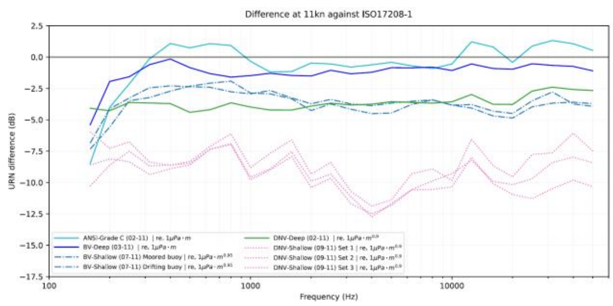


Figure 40: Difference of reported URN levels between ISO 17208-1 and the other procedures (Yubero de Diego *et al* 2023)

Transport Canada and VFPA (Vancouver Fraser Port Authority) initiated the 'URN Standardization Support' project to improve harmonization of URN measurement procedures, and to support the International Organization for Standardization (ISO) to develop a shallow-water URN measurement standard. The Enhancing Cetacean Habitat and Observation (ECHO) Program, initiated a second project concerning the alignment of URN measurement and analysis procedures used by ship classification societies for quiet ship certification.

Source level measurements using a drifting hydrophone array were analyzed separately from the other measurements (Figure 41). The overall quality of the drift measurements was poorer than the static measurements. This was partly due to increased self-noise, caused by wave-induced surface motion and currents, and partly due to difficulties controlling the measurement geometry caused by the relative motion of the source vessel and the measurement vessel.

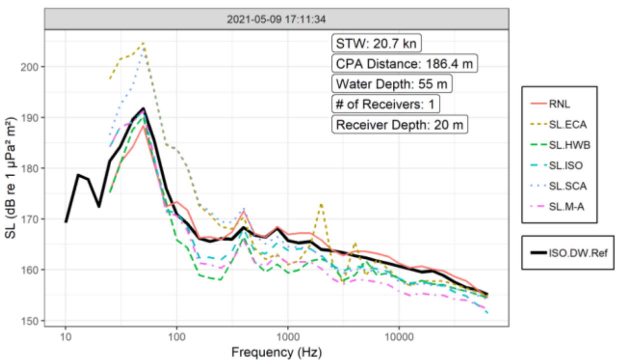


Figure 41: Source level (SL) measurements of vessel are performed at the shallow site using the drifting hydrophone array compared to the deep-water reference source level (Ainslie *et al* 2021).

ISO has recently been developing a standard for URN measurements in shallow water (ISO 17208-3/DIS:2024), which is also described in the ITTC Recommended Procedures and Guidelines 7.5-04-04-01, investigating the shallow water sound interacting with the seabed characteristics which are rarely known with accuracy. Depending on the water depth, sound may reflect one or more times from the seabed before arriving at the measurement points. Facilitating repeatable measurements in shallow water is expected to reduce the cost of obtaining quiet certifications (by reducing sailing time to a measurement location) and hence increase the proportion of the global fleet. To address the guideline for measurements in shallow water, the special requirements such as characteristic length, test site and hydrophone deployment, as well as various methods for assessing propagation loss are described below.

Since underwater ship noise is mainly due to machinery and propeller noise contributions, the ship characteristic length may be reduced to the distance between the machinery room and the propeller (Figure 42), rather than overall ship length. It is required in ISO 17208-3/DIS:2024 that length L is greater than 1/3 of the overall length of the ship L_{OA}.

$$L \leq L_{OA} \text{ and } L > L_{OA}/3 \qquad (4)$$

The ship source length L is also defined to solve the problem that the CPA (Closest Point of Approach) distance is too large for the measurements to get high enough SNR.

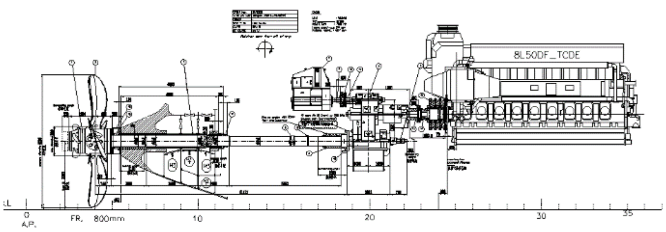


Figure 42: The dominant source of sound is main engine and propeller

For the test site, if the water depth is much smaller than the CPA distance, the water depth and seabed properties should be such that the lowest frequency of interest is at or greater than the shallow water cut-off frequency $f_{\min}$.The document 7.5-04-04-01 pointed out that shallow water effects can affect ship resistance and hence have influence on the ship radiated sound. This requires that the minimum water depth H_{min} for a ship of width B and draft T should be larger than $3\sqrt{BT}$. Figure 43 shows the minimum water depths according to ships overall lengths which were obtained from the marine AIS (Automatic Identification System) for vessels operating in the North Sea.

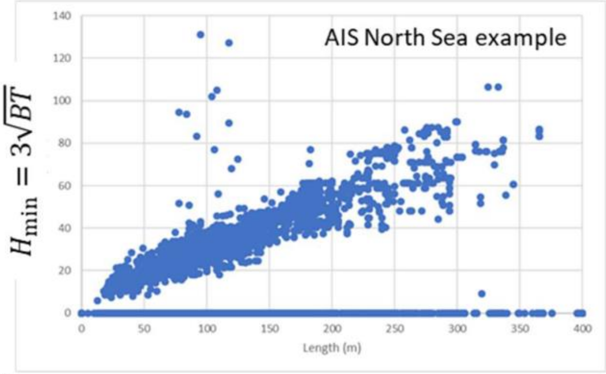


Figure 43: Minimum water depth according to ship length.

For water depths greater than the CPA distance, the hydrophone configuration specified in ISO 17208-1 applies. In water depths smaller than the CPA distance, a vertical array of at least three hydrophones, distributed over the water depth (Figure 44) is preferred.

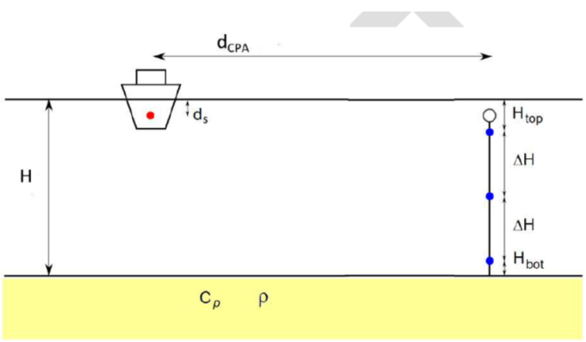


Figure 44: Proposed configuration for a vertical array in shallow water

For surface deployment, the wave drift will lead to a significant increase in low-frequency background noise. Also, the hydrophone deployed underwater is impacted by the water flow, and there is a strong flow noise interference. It is appropriate to apply measures to reduce the flow noise interference, such as those shown in Figure 45.

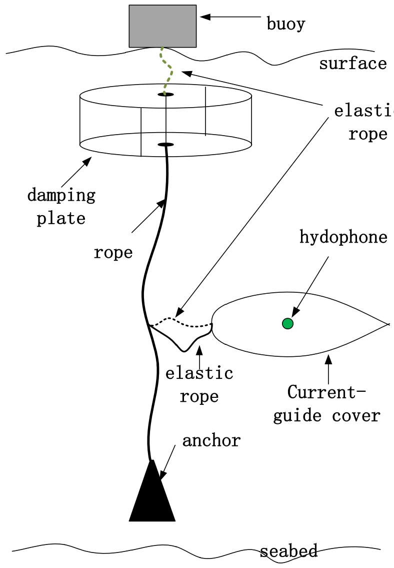


Figure 45: Measures to deploy hydrophone reducing the flow noise interference

Multiple methods for assessing propagation loss are provided: Seabed-critical angle (SCA) method (MacGillivray *et al*, 2023); Application of an empirical formula (as in ISO 17208-2) (Audoly *et al*, 2017; MacGillivray *et al*, 2023). The propagation loss assessment with an empirical formula is supported by measurements at the test site with a controlled acoustic source, as shown in Figure 46 (Pang *et al*, 2023).

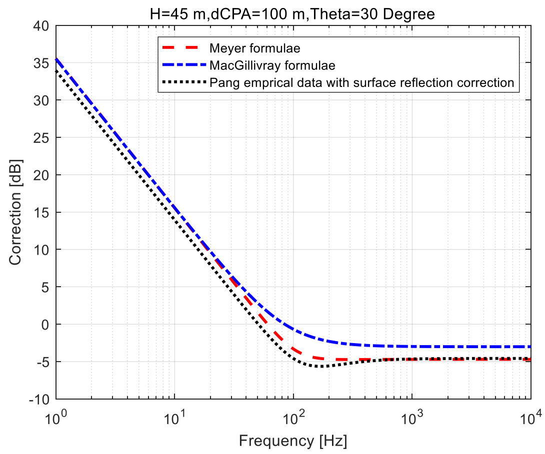


Figure 46: The empirical propagation loss corrections are compared (Pang *et al* 2023)

In addition to direct full-scale measurement in both deep and shallow waters, noise level evaluation methods based against on-board monitoring have been developed. Real-time evaluation of underwater radiated noise of merchant ships through on-board monitoring is a beneficial application that can reduce URN testing costs and is easily acceptable to ship owners. Meanwhile, it can monitor the ship's radiated noise for a long time and enrich the operational database, helping to optimize the design and operation.

Current on board methods used to estimate far-field noise from ships include: direct prediction methods based on hydrophones above the propellers; transfer functions derived from the relationship between measured vibration levels and sound source levels to optimize the number of sensors selected based on the contribution of the ship's sound sources, non-negative least squares (NNLS) methods (Basten 2015, Mulders 2018, Graeme *et al* 2021), the Operational Transfer Path Analysis (OTPA) method (Zerbs and Pascher, 2016); Average Quadratic Velocity (AQV) method based on the relationship between shell mean square vibration velocity and radiated noise transfer (Cintosun 2021); Energy Transfer Path Analysis (ETPA) method; Sound source level estimation from propeller characteristics (Bosschers 2017). These methods are known to be valid for propellers with or without cavitation.

Graeme *et al*. (2021) reported that ship's URN can be accurately estimated using NNLS values from on board accelerometers installed on the hull above the propellers and on possible machinery noise sources such as engines, generators and pumps. Figure 47 shows that the reconstructed URN using data from on board sensors agrees very well with off-board measured results.

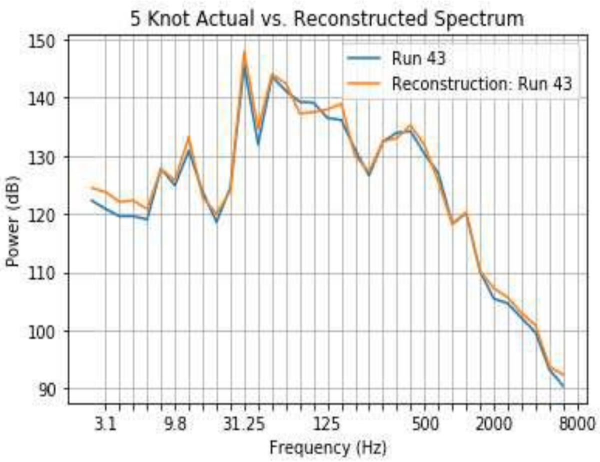


Figure 47: Ship radiation noise prediction results based on NNLS method (Cintosun *et al* 2021).

The OTPA-based method can be applied to submarine and surface vessel radiated noise prediction, but the prediction results can show a large deviation when there is a lack of certain equipment information, such as a source not equipped or not available as input to the method.

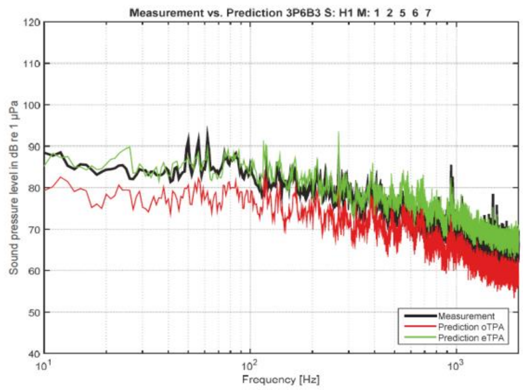


Figure 48: Ship radiation noise prediction results based on OTPA method (Zerbs and Pascher 2016)

4.2.3 Methods for hydro-acoustic modelling of noise

<u>Cavitation noise prediction</u>

Typically, propulsors are analyzed in open-water conditions, such as in a tunnel or in a free-field. Analyzes are commonly carried out at model scale. Some recent studies have considered the effects of the hull wake on the propeller hydrodynamics and acoustics, that is, by simulating propeller operation in the behind-the-hull condition. For most cases, validation data in terms of noise measurements is available. To capture the hydrodynamic sound sources, key physics need to be resolved, that is, flow turbulence and multiphase phenomena. The acoustics modelling approach should account for the propagation of the sound waves in the fluid medium, as well as the effects of the environment, such as the boundary conditions imposed by solid walls (hull, propulsor) or the free surface. The acoustic characteristics of the noise may also differ depending on whether the analysis is performed in a free-field or in a tunnel configuration.

Regarding turbulence modelling, the RANS approximation is frequently used in propeller analyzes. While propeller performance can be predicted well using RANS-based models, unsteady flow features, vortical flow and wake flow in general can suffer from a lack of detail. Tonal noise should be adequately predicted using RANS methods, but higher frequency noise content and the range of cavitation phenomena are usually more poorly represented, since these methods have limitations due to their averaging nature in resolving the turbulence fields and thus predicting broad-banded excitation. Scale-resolving models, such as large eddy simulation (LES) or hybrid RANS-LES based methods, such as detached eddy simulation (DES) or scale adaptive simulation (SAS) techniques, can resolve a part of the turbulent flow fluctuation spectra and thus also capture broadbanded sources of sound. In predictions of propeller cavitation performance and related sound levels, methods belonging to the DES category, such as delayed DES (DDES) or improved DES (IDDES), appear preferred and are frequently applied.

Most viscous CFD methods are based on a homogeneous mixture approximation that employs a volume-of-fluid (VOF) method to account for the water and vapour phases. Phase change is accounted for by mass-transfer models that are primarily driven by isothermal and incompressible pressure differences. The inability of mixture VOF models to resolve cavitation structures on small scales (on practical numerical grids), such as bubble growth and collapse, leads to the under prediction of the high-frequency content of the sound level spectra. Vapour structures resolution and turbulent flow are interconnected and high-fidelity cavitation modelling should be employed together with an appropriate turbulence modelling approach. A multi-scale multiphase modelling technique, such as the Eulerian-Eulerian two-fluid method (e.g., Li & Carrica, 2021; Viitanen & Peltola, 2021) or Eulerian-Lagrangian method (e.g., Wang *et al*., 2021; Lidtke *et al*., 2016), is likely needed for a more complete representation of various cavitation types and dynamics. These currently remain as research topics, although some applications have been reported. An Eulerian-Eulerian two-fluid method has been recently applied to study cavitation noise on static hydrofoils (Hynninen *et al*., 2023), and the results were compared to those with the VOF method and experimental measurements. Ku *et al*. (2022) applied a sequential, one-way coupled Eulerian-Lagrangian bubble model to predict tip vortex cavitation inception and noise. They performed an unsteady RANS simulation to obtain tip vortex trajectories where they inserted Lagrangian bubbles to predict TVC inception and resulting noise (Figure 49). Cavitation noise was predicted by modelling the bubbles as point monopoles, and the resulting pressure spectra were compared with measurements (Figure 50).

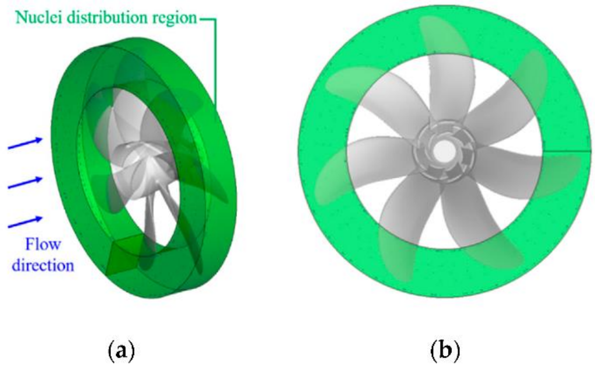


Figure 49: Distribution domains of nuclei (Ku *et al*. 2022).

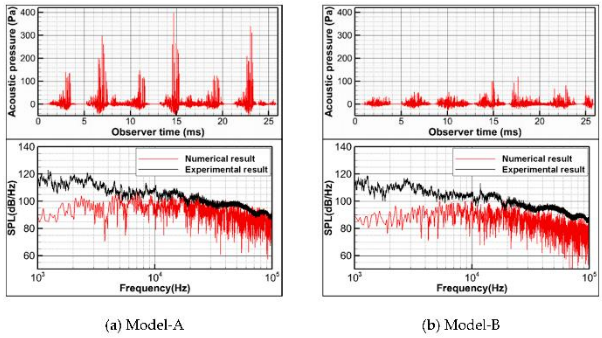


Figure 50: Acoustic pressure due to tip vortex cavitation in the time and frequency domains (Ku *et al*. 2022).

Typically, cavitation propeller noise predictions using CFD and CHA (computational hydroacoustics) methods are based on the Ffowcs Williams Hawkings (FWH) acoustic analogy (e.g., Fujiyama & Nakashima (2017), Li *et al*., (2018), Sezen *et al*., (2020, 2021a, 2021b), Ku *et al*. (2021), Lidtke *et al*., (2022)). There are variations in specific numerical techniques applied in this CHA class, frequently referred to as direct and permeable (or porous) formulations for the acoustic analogy (Wang *et al*., 2022). With the direct method, one evaluates the Lighthill stress tensor directly with a volumetric integration. The permeable formulation closes the main sound sources with a data surface, and noise generation within this surface is idealised by virtual sources on the surface. The latter approach is most frequently used. As noted by Cianferra (2017), the permeable formulation predicted the main frequency components although with underpredicted amplitude and sensitivity to the position of the surface, while the direct approach provided a noise prediction very similar to reference data everywhere in the field. Recently, Wang *et al*. (2022) proposed an interesting dual-mesh technique for the direct FWH analogy for propeller noise simulation, that reduces the calculation time and required computer disk storage space (Figure 51). Lyu *et al* (2023) demonstrated that with careful positioning of the data surfaces for a cavitating propeller case, similar results can be predicted in terms of monopole noise spectra using the permeable formulation. On the other hand, Viitanen *et al*. (2018) have applied a FEM based Lighthill analogy for noise simulations of wetted and cavitating propellers, which utilised both volumetric sources near the propeller and a conformal surface enclosing the propeller, with source data from a DDES-based solution. This method was also used to predict non-cavitating noise from a thruster unit in-behind conditions and the results were compared to full-scale noise measurements (Viitanen *et al*., 2023).

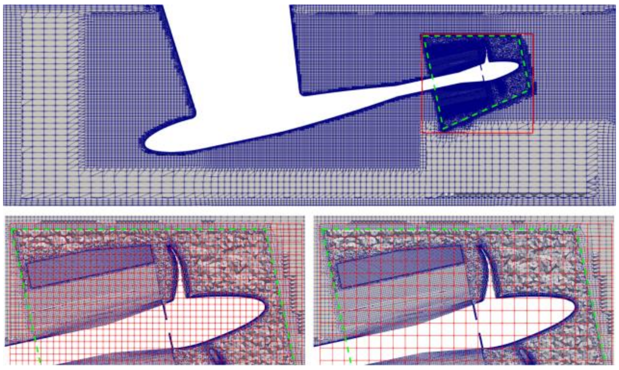


Figure 51: CFD (blue) and acoustic (red) meshes (Wang *et al*. 2022).

Li *et al*. (2018) applied a DDES based flow solution together with a permeable FWH formulation to predict URN. The results were compared to model-scale and full-scale noise measurements (Figures 52 & 53). They demonstrated that the numerically predicted pressure pulses and tonal noise closely correspond to the measured data for the first five orders of blade passing frequency. Low-frequency (< 112 Hz) broadband noise was underestimated, which was attributed to under-resolved tip vortex cavitation.

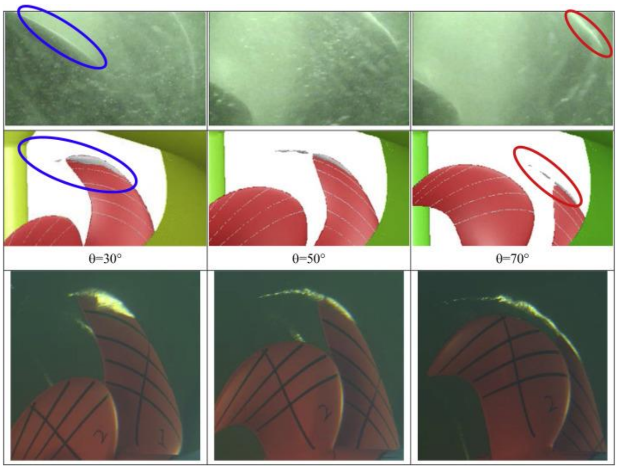


Figure 52: DDES prediction of cavitation (middle row) and comparison to sea trials (top) and model tests (bottom) (Li *et al*. 2018).

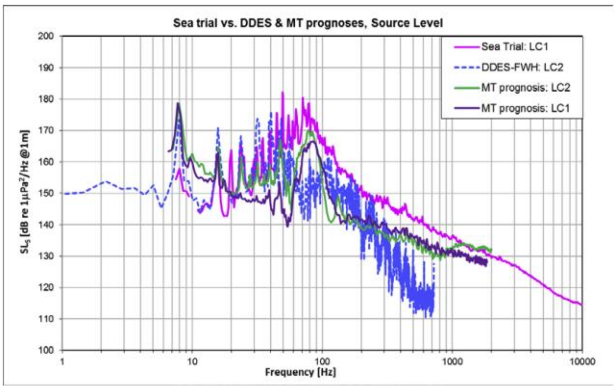


Figure 53: Full-scale noise source levels based on different methods (Li *et al*, 2018).

Lidtke *et al*. (2022) applied a permeable FWH acoustic analogy, using an IDDES method for the flow solutions to resolve part of the turbulence spectra and cavitation dynamics. They showed that low-frequency peak sound pressure levels can be predicted to within 5 dB of measurements, and that key features of the shape of the noise spectra can be well represented with the simulations. They also bring up an interesting point that has not been widely discussed, that is, the CFD method generates background noise that can be significant in certain conditions or frequency ranges. To address this, they propose that determination of numerical background noise should be a part of the URN assessment.

Sezen *et al*. (2021a) investigated the influence of several RANS-based turbulence models, and a permeable formulation for the FWH acoustic analogy was applied to evaluate the resulting noise. They noted that the RANS models predicted similar noise levels at low propeller loading, and that at high loading more discrepancies were seen.

Sakamoto & Kamiirisa (2018) applied two different noise prediction methods based on viscous CFD solutions with DES. In the first method, they used the time domain pressure predicted by the CFD solver at certain probe points, to resolve blade passing frequencies and a limited range of broadband noise. In the second method, they applied Brown's formula (Brown, 1976) together with the CFD simulation. The Brown's formula is an empirical relation with, e.g., the propeller diameter, number of blades and rate of revolution as parameters, and information of the cavitation volume predicted by the CFD solver was used. They concluded that methods estimate the tonal noise up to the 3rd blade frequency well, and that Brown's formula predicted the upper bound of broadband noise. A similar approach was also used by Fujiyama & Nakashima (2017), who also compared the results to the FWH acoustic analogy solution and to full-scale measurements. They noted that the results with the direct pressure analysis were in good agreement with measurements and with the FWH method. Comparison with experiments was favourable up to the 5th blade passing frequency in model-scale, and in full scale up to approximately the 2nd blade passing frequency due to challenges in resolving the tip vortex cavitation in full-scale simulations. It was challenging to reliably predict noise levels using CFD calculations alone at higher frequencies. Consequently, the empirical formula was suggested to be applied in conjunction with the CFD results.

<u>Noise propagation modelling, especially for shallow waters</u>

Several numerical methods exist for modelling noise propagation. Based on their accuracy and practicality, Etter (2009) and Farcas *et al*. (2016) have reviewed various propagation models that are currently in use. Underlying mathematical methods, including ray theory, normal modes, multipath expansion, wavenumber integration, and parabolic equation, have been used to divide the propagation models. The methods can be classified based on their ability to predict propagation in different depths and frequencies (Figure 54). The models can be further categorized as range-independent (depth-dependent) and range-dependent models. For instance, with ray theory applicability is better in deep water at low frequencies where there are less reflections from the bottom and the surface. At high frequencies in shallow water the applicability is worse in range-independent environments. Parabolic equation (PE) methods allow a weak range dependence, though at high frequencies, the model typically becomes impractical due to excessive execution times, especially in shallow water where the strong bottom interaction demands shorter range steps.

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 nor practical

Figure 54: Domains of applicability of different ocean-acoustic propagation models (Etter, 2009).

Deavenport *et al*. (2019) have developed a ray model with a convolution-based time-domain procedure to simulate transient signals that propagate in shallow-water environments. Zhou *et al*. (2021) developed a two-dimensional FEM for predicting propagation of sound. The method was applied to different environments, and results compared to other benchmarks, analytical and numerical solutions.

Liu *et al*. (2021) applied a few numerical methods to estimate transmission loss (TL) in shallow water with varying bathymetries, and compared the results to measurements (Figure 55). Forms of TL in different frequencies were analyzed with respect to the varying characteristics of the seabed and the underwater environment. Sipilä *et al*. (2019) applied a propagation model based on the PE method to predict transmission in very shallow waters (depth 25 m) and compared the results with full-scale noise measurements. They also investigated the sensitivity of transmission loss to bathymetry and seabed sediment characteristics (Figure 56). It was observed that the measured and simulated transmission loss levels were similar and showed an increasing trend towards higher frequencies.

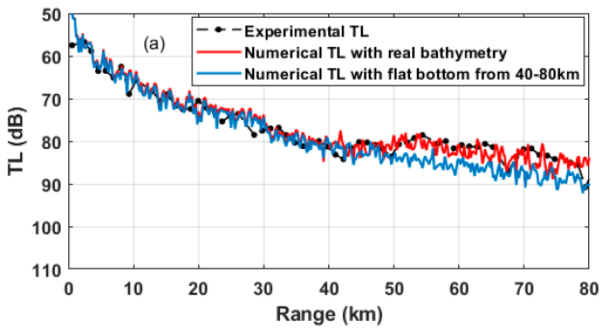


Figure 55: Comparisons of experimental and numerical TLs (Liu *et al*, 2021).

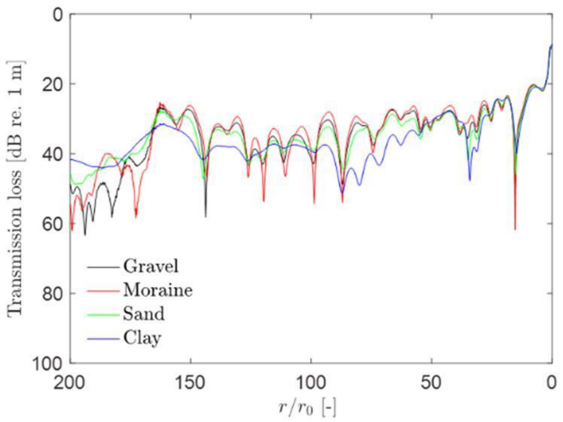


Figure 56: Comparisons numerical TLs for different bottom sediments (Sipilä *et al*, 2019).

Küsel & Siderius (2019) compared several different propagation models. They studied the same test cases as were applied in a sound mapping workshop (Colin *et al*., 2015), with range-independent and dependent cases, and comparisons of propagation loss (PL), sound exposure level (SEL), and pressure in the time domain (Figure 57). They noted that a PE would likely be a method of choice for a range-dependent environment, and that ray-based theory was not appropriate for shallow water waveguide based also on errors in broadband SEL. They also pointed out that experienced propagation modelers know intrinsic details of each model, however, for occasional users who want to know what the sound field looks like given a specific source and environment and if sound levels are too high such that they may harm marine organisms, many details regarding their model of choice may not be obvious or intuitive.

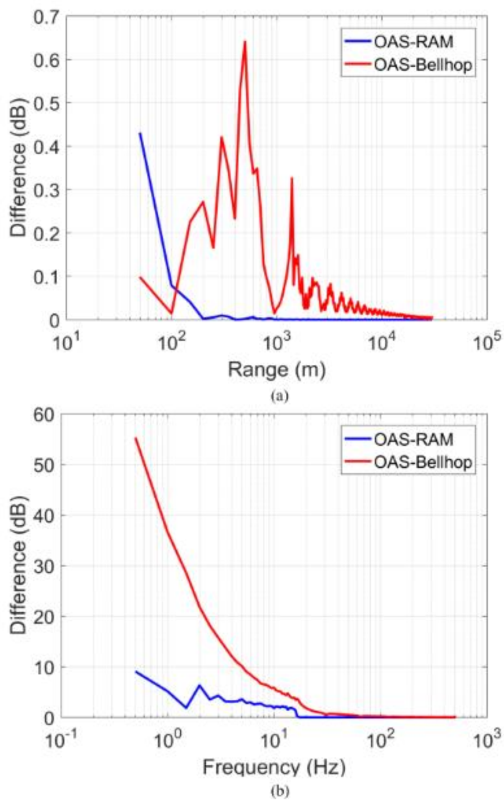


Figure 57: Mean absolute errors of sound exposure levels vs. range (a) and frequency (b) between different numerical methods (Küsel & Siderius, 2019).

Oliveira *et al*. (2019) presented a comparison of different methods in idealised cases (2D and 3D) with varying complexity (Figure 58). Moreover, the PE model was applied in a shallow water environment, with the environment being extremely complicated, especially the highly variable bathymetry. They noted that transmission loss (TL) results provided by the PE, normal mode, and beam tracing models tended to agree with each other, although differences can result with increasing the bathymetry complexity and expanding the range of propagation. The low-frequency cases of 500 Hz in such shallow water were below the threshold of a ray or beam model's validity. They noted that when choosing an underwater sound propagation model for practical applications in complex shallow water environments, a compromise must be made between numerical model accuracy, computational time, and validity.

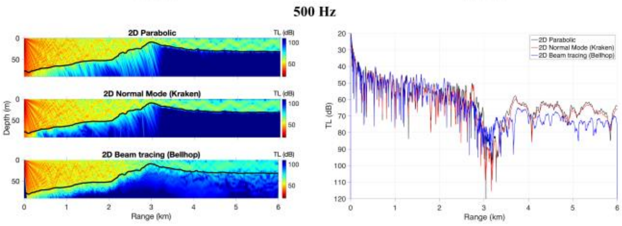


Figure 58: TLs based on different numerical methods (Oliveira *et al*, 2019).

4.2.4 Noise in ice conditions

The rapid loss of summer sea ice that's been observed in recent years has opened up ship traffic to this once nearly inaccessible region. Low-frequency sounds generated by ships propagate efficiently and travel long distances in deep marine environments such as polar regions.

<u>Noise propagation under ice condition</u>

Noise propagation in ice conditions is different from non-polar regions. At high latitudes, noise from a ship is particularly efficient at propagating over long distances due to the Artic sound channel (see Figure 59), similar to the SOFAR (Sound Fixing and Ranging) channel. Frequencies between 15 and 30 Hz travel most efficiently through the Arctic sound channel, and high frequency sounds do not propagate as far as lower frequency sounds. Sound propagates much farther in the SOFAR channel compared to the Arctic sound channel, because sound waves in the Arctic sound channel may also interact with the ice, and therefore increase attenuation. However, the Arctic sound channel allows for farther propagation distances at shallow depths (100 to 300 m) compared to non-polar regions.

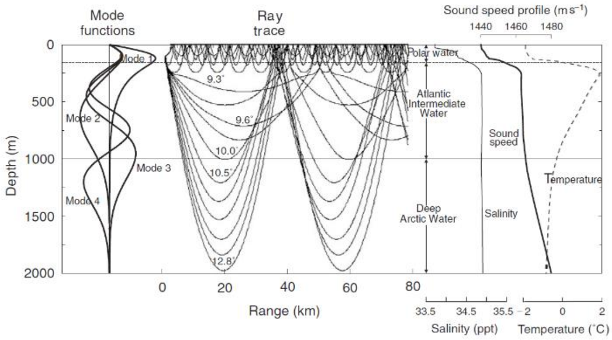


Figure 59. Ray trace in Arctic sound channel (Mikhalevsky, 2001).

<u>Noise from collision of propeller and ice</u>

According to available studies, the main noise source during icebreaking seems to be propeller cavitation (Almgren 1991; Erbe 2000; Roth 2013), icebreakers generate higher and more variable noise levels from propeller cavitation compared to other vessels due to the episodic nature of ice breaking, which often involves manoeuvres such as backing-and-ramming into the ice.

A study of the United States Coast Guard (USCG) Cutter Healy's URN signature during ice breaking operations was reported in Roth (2013). Compared to open-water transiting, the noise signature increased approximately 10 dB between 20 Hz and 2 kHz when breaking ice (Figure 60). Operating ahead, even when breaking ice, does not typically produce high noise levels. There are two scenarios that generate considerably higher noise levels, when propellers are operated in opposite directions; and during backing and ramming when the propellers are operated astern, particularly when the ship begins to impact the ice.

Some icebreakers are equipped with bubbler systems that blow high-pressure air into the water to push floating ice away from the ship, creating additional noise over short ranges (Roth, 2013; Erbe 2000). Its noise characteristics are temporary continuous with a white noise spectrum with most of its energy below 5 kHz. The reported source level spectra from ice-breaking operations (Roth, 2013; Erbe 2000) are typically 10 to 15 dB higher than what can be expected for a conventional LNGC in open water.

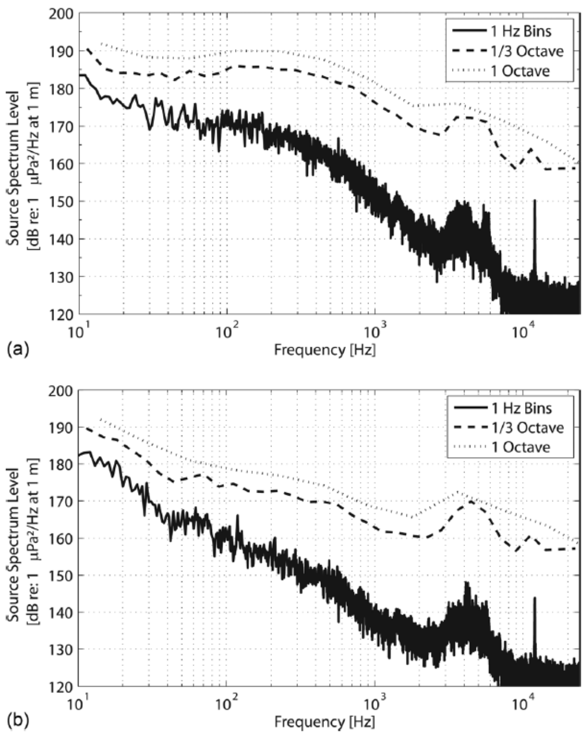


Figure 60. During August 27 transit: (a) estimated source level of Healy transiting in 8/10's ice cover at 05:26:30; range to the sonobuoy was approximately 2 km. (b) Estimated source level of Healy transiting in 3/10's ice cover at 05:51:20; range to the sonobuoy was approximately 4 km (Roth *et al* 2013).

Underwater noise from the Swedish icebreaker ODEN was measured east of Greenland in 1990, Almgren (1991). The propeller was found to be the primary acoustic source and the most intense noise levels were produced when the propeller nozzles clogged with ice causing stagnation of the inflow to the propellers, resulting in increased cavitation. The source levels, were reported to be roughly the same as from other icebreakers, but much higher than noise levels from ordinary ship operations in open water, as shown in Figure 61. The source levels also seem comparable to more recent studies, e.g. Roth (2013) and Erbe (2000).

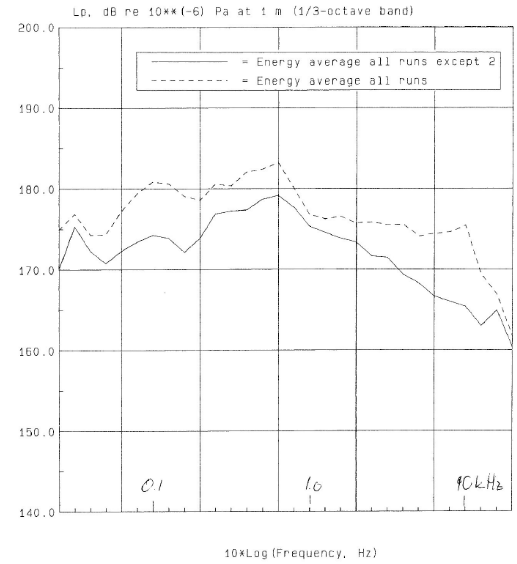


Figure 61. Source Level of Swedish icebreaker ODEN during ice-breaking operations in August 1990, with and without the two noisiest series (Almgren 1991).

The predicted receiver level at various distances is shown in Figure 62. At 1 and 10 km distances the sound pressure level is well above the ambient noise. The sound pressure level was found to be below the measured ambient noise at 100km distance, except in the range 20 to 40 Hz where the levels may be above the ambient noise also at 100 km; Only Baleen whales are known to produce sound in this frequency range.

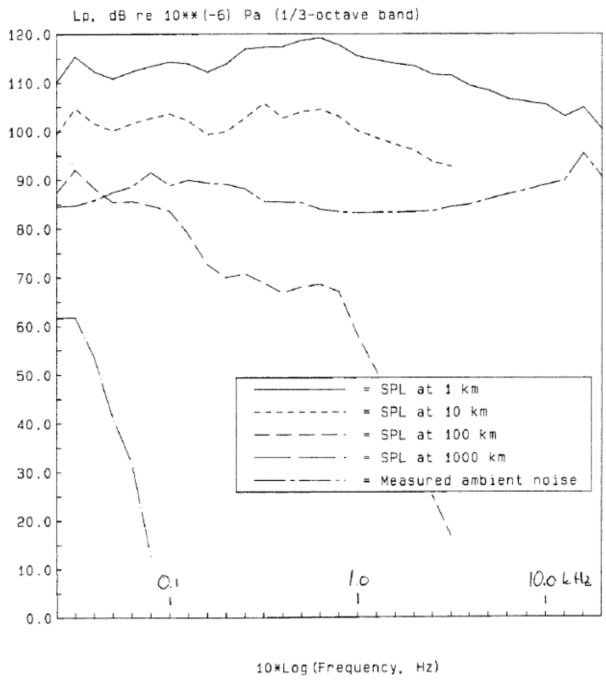


Figure 62. Prediction of ice-breaking noise from Swedish icebreaker ODEN at different distances (Almgren 1991).

4.3 Vibrations

Tor #8 was dedicated to the review of open literature dealing with the respective contributions of the hull vibrations and of the propeller in the ship radiated noise at full scale (frequency line and broad band spectrum) and investigate ways of assessing those contributions.

As previously reported in the 29th ITTC Specialist Committee on Hydrodynamic Noise Final report, the noise caused by vibrating machinery onboard a ship is called structural borne noise with the first path of vibrations being transmitted through the ship structure to the outer plating resulting in radiated noise. The secondary structural path is excited by the airborne noise that impinges at the compartment boundaries and excites the structure to vibrate. These vibrations propagate to the outer plating causing underwater noise.

The intent of the literature review is to understand the extent of full scale ship measurements undertaken to understand the contribution of hull vibrations and the propeller. In general propeller cavitation is the significant component of broadband noise and propeller singing (tonal type) and other ship sources are considered narrowband. Figure 63 taken from (Crocker, MJ, 1998) shows typical frequency contributions to ship acoustics.

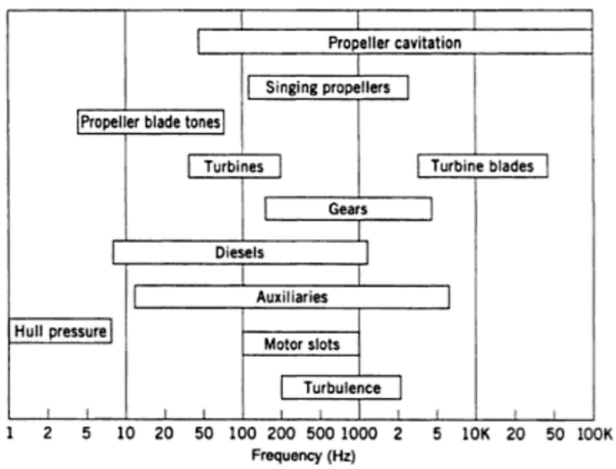


Figure 63: Ship Noise Sources (Crocker 1998).

There are a limited number of available papers in the open source domain looking at the contribution of structural borne noise from ships based on full scale ship trials. Zhang *et al* (2019) published a paper comparing different radiation modelling for the structural borne noise of an oil tanker. The paper discusses the three major contributions to underwater noise sources: mechanical noise, propeller noise and hydrodynamic noise of which the mechanical and propeller are most significant. The paper only considers underwater radiated noise from hull vibration due to the main power plants in the engine room. Foot vibration accelerations of the power plants were obtained on the full scale ship. In addition, vibrational acceleration measurements were acquired on local parts of the oil tanker for comparison with simulation results.

The structural borne component was compared using different acoustic models at low and mid-frequencies;

- The finite element and boundary element method (FE-BEM)
- Finite Element and infinite element method (FE-IFEM)
- Finite Element and automatic matching layer (FE-AML)

In the paper's conclusions it was found for this ship that the FE-BEM is the preferred method for estimating ship underwater radiated noise. The high frequency components performed using the statistical energy analysis (SEA)

The oil tanker vibration calculated values agree well with the measure values. Figure 64 shows the comparison of simulation and measured engine room vibrations.

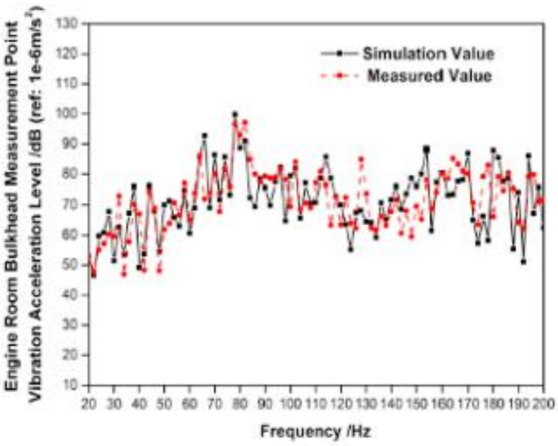


Figure 64: Comparison of simulated and measured values for Engine room measured location.

Rodrigo-Saura *et al* (2017) look at the transfer function (TF) of the structure-borne noise to underwater radiated noise for a vessel constructed of glass fiber reinforced plastics (GRP) and one constructed of steel.

Full scale measurements were obtained from two fishing boats, the GRP vessel being 23m length and the steel 24m. The vessels were instrumented up with accelerometers and data was acquired simultaneously with URN measurements.

Figure 65: Fishing boat full scale measurements.

The TF relates to the structure borne noise level of the hull with the underwater radiated noise (URN). The intent being the acoustic noise generated by the vibrations of the hull could be estimated from real time measurements of the structure-borne noise levels of the hull by applying the TF in real time. From the conclusions it verified that parameters such as the ambient noise, size of the vibrating panels and position of sensors must be taken into account to estimate the TF. Figure 66 compares the mean transfer functions for both hulls for both Broadband and Narrowband.

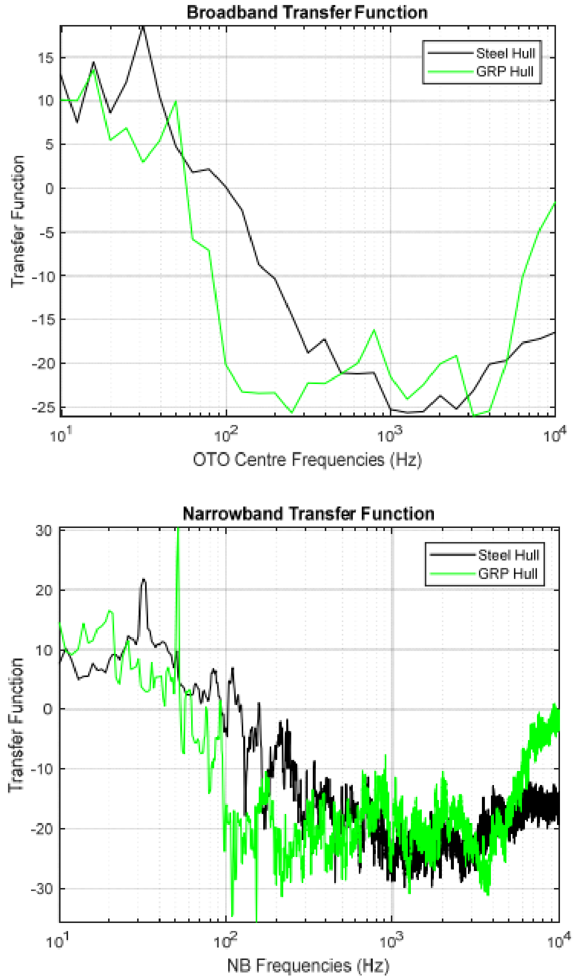


Figure 66: Broadband (top) and Narrowband (bottom) mean transfer function of the measurements of the ship with steel and GRP hulls.

A further paper (Lee *et al*, 2024) investigates experimental validation of a numerical procedure for estimating the structure-borne URN transfer function of a marine structure based on Statistical Energy analysis. (SEA). The transfer function method is considered as a countermeasure by classifying the URN generation mechanism into the sources and the propagation paths to predict the ship URN levels through a simple summation of various URN contributions. The experimental validation was originally undertaken on a fluid-loaded four-edge stiffened plate of 1.44m long and 0.71m wide as seen in Figure 67 and an exciter mid panel representing the mechanical power.

Figure 67: Stiffened plate fabricated for validation tests.

The results of the structure-borne URN TF's estimated by the SEA and experiments are shown in Figure 68.

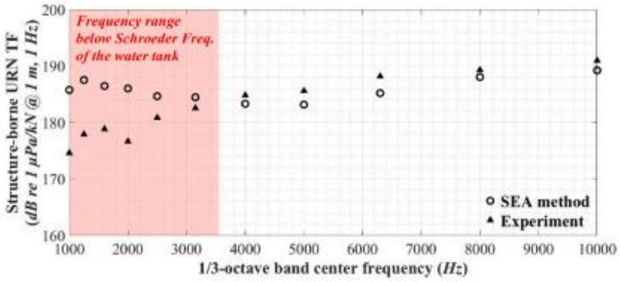


Figure 68: Structure Bourne URN TF's estimated by the SEA and experiment 1-10 kHz

Full scale measurements were conducted on a 65.4m Korean Research vessel, 'Cheong-Hae' to confirm the practicality of the proposed procedure. The structural borne URN of the vessel and the predicted measurements are shown in Figure 69.

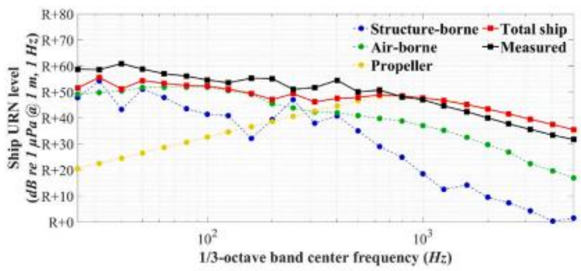


Figure 69 Total ship URN levels evaluated by the SEA and sea trail measurements. (25Hz-5kHz)

Under the collaborative project AQUO, (Achieve Quieter Oceans by shipping noise footprint reduction), a measurements task was undertaken (AQUO D3.3 2014). The contents of the paper details ship types and methods used to acquire accurate experimental data for analysis of the URN signatures of each vessel. The intent was to collect data for the contribution of each noise source on the vessel. Table 1 provides the list of full scale measurements made for the AQUO project.

Partner	Vessel type	Measurement Activities							
		Hull	Machinery	Calibration	URN	Directivity	Cavitation visualization	Power	AIS
TSI	FRV (FS1)	X	X	X	X	X		X	X
TSI	RV (FS2)	X	X	X	X	X			X
TSI	Commercial (FS3)	X	X	X	X	X		X	
TSI	FV (FS4)			X	X	X			
CTO	Research Vessel (FS5)	X*		X	X		X	X	X
SSPA	Coastal Tanker (FS6)	X*	X	X	X	X	X	X	

Table 1: Full scale measurement undertaken.

The aim of the hull and machinery vibration measurement is the correlation of the on board vibration phenomena with the narrow band spectra obtained during the URN measurements. The intent is to, in the future, report the different sources of the underwater footprint of the vessel. Therefore, the AQUO project should be monitored for any further open source literature by this ITTC committee.

From the open source data currently found, Figure 69 provides the only actual breakdown of components showing URN contributions. It is likely that with URN being of high priority for Naval vessels further work has been conducted assessing the contributions of structural acoustics but this data tends to be at a classification not available as open source information.

4.4 Benchmark tests

4.4.1 JoReS activity

CFD methods have been confirmed as a potential on ship hydrodynamic prediction. While being a flexible and low-cost tool, its results are subject to model test validation, as it offers a well-controlled, physical measured value.

Striving to increase confidence in numerical methods and create a basis to further ship performance improvement and industry digitalization, a group of key companies and research institutes have now stepped up to close this knowledge gap between model tests, CFD and full-scale reality and joined the Joint

Research Project: Development of an industry recognized benchmark for Ship Energy Efficiency Solutions (JoRes).

JoRes (www.jores.net) aims to increase the understanding of full-scale ship hydrodynamics by comparing the state-of-the-art ship hydrodynamic measurement techniques (model test results, CFD calculations and ship scale measurements including PIV propeller flow measurement).

One of the main tasks of the JoRes project is to develop a full set of industry recognized benchmark cases for full-scale and model-scale validation of CFD computations. The target goal is to increase knowledge on the important propeller/hull interaction effects, build confidence in ship scale CFD and assess their performance compared to traditional model testing.

The existing MV Regal vessel (Lpp=138 m) was selected as the first validation test case. The JoRes project organized several workshops to compare the full-scale results of CFD computations with the sea trial measurements conducted in September 2020 on the single screw general cargo vessel Regal. The primary objective is to assess and enhance the predictive capability of numerical simulation tools in ship scale.

Figure 70: Test (a) and simulation (b) geometry model of general cargo vessel REGAL; (Song *et al*., 2021)

Blind CFD computation results from different companies were compared either to empirical friction lines proposed by literature (flat plate and viscous hull resistance), calm water model tests (propeller open water data and cavitation), sea-trials data (hull and propeller roughness, resistance, and propulsion), direct and statistical comparison by the CFD data (resistance, propeller open water data and self-propulsion).

Although the presented CFD results were within the range of the experimental results, a big spread in the submitted data was shown between different numerical solvers. Therefore, it was suggested to investigate the details of all possible reasons that cause this difference. It was decided to investigate deeper every case separately and allocate a meeting to discuss the results for each case.

Flat plate simulation is the simplest form of the presented CFD simulations. The mesh error effect was excluded by asking the participants to compute using the same provided mesh. After discussing the results, a common relevant procedure (turbulence model, wall treatment and boundary conditions) to conduct CFD computations on a flat plate was established.

The second test was the ship resistance at full-scale without implementing hull roughness (smooth hull roughness). Similar to the smooth flat plate case, the results for the smooth resistance case showed a spread of about 40%.

To identify systematic deviations between the CFD-methods, it was proposed to conduct a series of mini workshops and evaluate the data (starting from the simplest to the most complex case) and make sure each step leads to an accurate procedure for resistance computation at full-scale. The new procedure is based on some predefined settings (excluding at this stage the superstructure and propeller blades). For this case, it was requested to generate the mesh individually, while respecting the imposed methodology; given domain size, thickness of the first cell on the hull and using the k-ω SST turbulence model. During the mini workshop dedicated to this first case, it was concluded that a proper procedure to conduct the smooth hull resistance at full-scale and improvement of the results was seen compared to the experimental data.

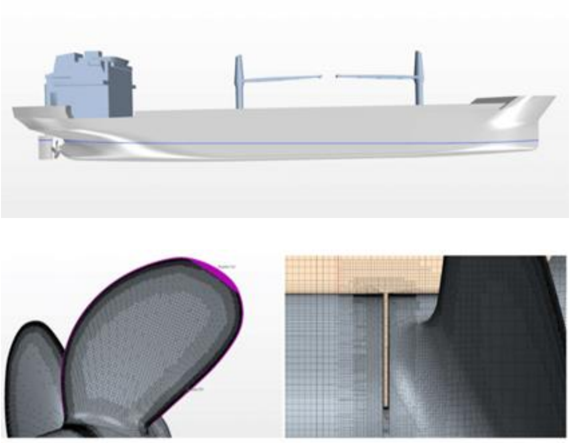
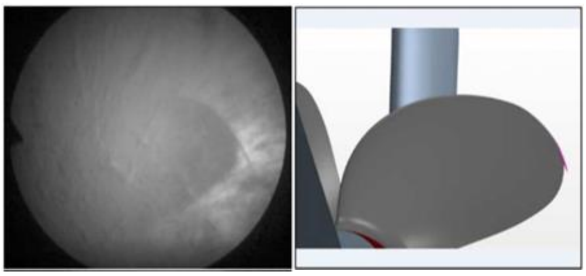


Figure 71: Geometry assembly of the MV REGAL used in self-propulsion simulations. Blue line shows the free surface level at the initial hydrostatic position; (Krasilnikov *et al*., 2023)

To simulate sea trials numerically in CFD, it is important to know the actual roughness characteristics of the hull and propeller. The JoRes team has been conducting a study on how to derive the roughness coefficients for the ship hull and propeller. Therefore, instructions and guidelines on numerical calculations have been shared with the working group.

The RANS self-propulsion simulation conducted with the measured hull roughness was extended with a cavitation simulation using a phase change model by Krasilnikov *et al*., 2023. The cavitation images obtained from the simulation were compared with borescope video taken during the sea trials.

After the first successful case, the JoRes 1 tanker (Lpp=178.5 m) has been selected as the second benchmark candidate. Similar exercises have been conducted and the computational speed/power results (Resistance, Torque, Thrust, Speed, Rpm, Cavitation observations and pressure pulse measurements) have been discussed in several CFD workshops.



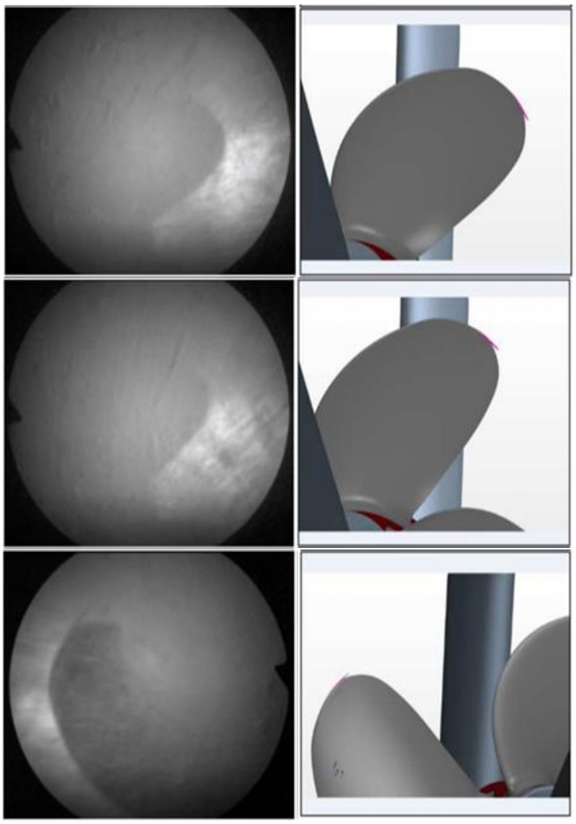


Figure 72: Comparison between the numerical simulation and full-scale observations on propeller cavitation; (Krasilnikov *et al*., 2023)

Direct comparison of the twin-screw propulsion performance is a good example to improve understanding of the model tests correlation and reduce the inherent numerical accuracy and uncertainties in modelling the exact trials conditions. The JoRes 2 ferry vessel, a twin-screw RORO ferry, is equipped with Controllable Pitch Propellers. so, there is always uncertainty about the actual pitch angle at the time of trials. Significant efforts were made to minimize this uncertainty, nevertheless, it is still not zero. That is why two sets of propellers with different pitch angles (-9.5 deg and -10.5 deg) have been offered.

To provide high-fidelity sea trial data for CFD validation, extra benchmark cases have been made available by the JoRes project, namely: the JoRes3 Cruise Liner (two 5-bladed fixed pitch propellers) and the JoRes4 Denis tugboat (two 4-bladed ducted propellers). For each benchmark case, the CAD geometry is cleaned and prepared for CFD validation along with providing the results of model tests and sea-trials data.

The JoRes Joint Industry project was successfully completed on the 1st of December 2023. Within the project 6 ship-scale validation cases were developed and all the results and geometries will be publicly available from the 1st of December 2024 (free registration on the JoRes website will be enabled).

As a follow-up to the success of the JoRes project, Chalmers University of Technology is introducing the seventh validation case and organizing a blind CFD workshop (Open Workshop on Ship Scale Resistance Prediction) full-scale and model-scale resistance prediction. The CFD results will be compared with measurements for different model scales and full-scale as well.

4.4.2 Round Robin Test on Cavitation Noise

The Round Robin Test Case, described briefly below, is the one selected by the previous 29th ITTC Specialist Committee on Noise.

Ship characteristics

In Figure 73 a photograph of the ship is reported, while the main ship characteristics are listed below.

Figure 73: Nawigator XXI Research Vessel

- Ship name: Nawigator XXI
- Type / Year of building: Research Vessel built in 1998
- Owner: Maritime University of Szczecin
- Length overall: 60.3 m (LOA)
- Beam: 10.5 m
- Draft: 3.15 m
- Displacement: about 1150 t
- Speed: 13 kn (max)

Propulsion plant and other machineries characteristics are listed below:

- 1 Controllable Pitch Propeller (CPP), D = 2.26 m, P/D(design) = 0.942, 4 blades
- Main Engine: SULZER Cegielski 8S20D (4 stroke, 8 cyl L) resilient mounted, 1120 kW, 900 RPM, reduction rate: 3.75
- Auxiliary Engines: Caterpillar SR4: (4 stroke, 8 cyl L) resilient mounted, 2 x 240 kW + 1 x 85 kW, 1500 RPM
- Bow thruster: 110 kW, abt. 500 RPM (propeller)

URN measurements at sea have been carried out during the EU-FP7 AQUO project; the campaign took place in the Baltic Sea and the following data was recorded:

- Shaft power, rpm, pitch, speed over ground
- Cavitation observations
- Vibrations
- URN
- Pressure pulses

Measurements have been performed at one ship draught (3.2 m at stern, 3.15 m at bow), propeller pitch was varied at constant RPM (8 different pitch settings); in addition to this, at one pitch setting two different propeller RPMs have been considered.

Documents for the benchmark have been written. It contains:

- Memo document with the presentation of the test cases
- ITTC Agreement that each participant is required to sign that they comply with the requirements of sharing results within ITTC
- Nawigator geometry
- Propeller at two different pitches
- Hull geometry

Three main conditions have been chosen for the propeller operating conditions. They are summarized in Table 2

Condition	P/D	K_T	$\sigma_{N\ (tip)}$
A1[9]	0.91	0.22	2.79
A2	0.91	0.26	2.79
A3	0.91	0.22	4.2

Table 2: Mandatory conditions for the proposed benchmark

The tests have to be performed in accordance with the participant's normal procedures.

4.4.3 Numerical benchmark possibilities

The Nawigator case has been recently chosen as the test case for the numerical benchmark Wageningen CFD 2025 workshop (as successor to previous CFD workshops). This benchmark appears to be a good opportunity to exchange results on the same test cases. Comparison of experimental results at model-scale, full-scale results and simulations is important.

5. SUMMARY AND CONCLUSIONS

The conclusions of the 30th Specialist Committee on Cavitation and Noise are presented here, ordered by the Terms of Reference.

1. All procedures and guidelines have been updated. A global document, based on the procedure 7.5-02-03-03.2, has been extensively updated to give a common base for all the other procedures and guidelines. It has been renamed "Visual description and measurement of cavitation events". It proposes global features and a common description of the cavitation events that could be observed in many configurations. Moreover, the two guidelines on erosion (7.5-02-03-03.5 and 7.5-02-03-03.7) have been merged into one document.

2. An extensive review of the recent studies dealing with cavitation has been presented. Most of them are dedicated to cavitation and noise measurements. Accuracy is generally not investigated by authors and remains an important task to conduct in the future.

3. A review of existing methods for cavitation simulations is presented. A questionnaire about dummy model practice has been distributed. Results obtained thanks to many institutes have been analyzed and are presented in this report. Due to the important differences between the practices, writing a guideline for "Dummy model practice" seems to be a difficult task.

4. Among all the benchmark data for CFD investigated, only JORES has been found available for sharing data (data available at end of 2024). Discussions with Wageningen Workshop 2025 for the definition of the test case on cavitation have been lead. The Nawigator XXI test case has been identified as a particularly interesting case and links with the Round Robin Test could be made between results at full-scale, model-scale and CFD.

5. A review of recent studies with different optical techniques using cameras and laser as well as non-optical approaches is presented. Applications of such techniques at full-scale have also been reported for cavitation and/or noise.

6. The process for the organization of the Round Robin Test proposed by 29th Specialist Committee on Hydrodynamic Noise has been defined. Formal agreement for sharing the hull geometry is still lacking (the only point that prevents launching the benchmark).

7. Some progress on acoustic features at model-scale have been reported. They concern particular aspects of acoustic or techniques with several sensors. It is worth noticing that a new method for scaling Tip Vortex Cavitation will be published in 2024.

[9] For this condition full scale measurements are available; propeller revolution rate at full scale was 230 RPM, with a correspondent $\sigma_{N\ (shaft)} = 3.09$

8. There are a limited number of available papers in the open domain looking at the contribution of structural borne noise from ships based on full scale ship trials. The review of these papers is presented.

9. An update of ISO and classification society rules has been made. The procedure for full-scale noise measurements has been updated thanks to the recent studies and methods developed for shallow water configurations.

10. A review of the recent studies and methods used for CFD noise prediction is presented in the report. Examples of recent literature are presented in this document focusing on the applicability of the method to the case investigated.

Finally, the ITTC Specialist Committee on Noise has submitted a document to IMO during the development of their circulars: "ITTC 2023, Review of full-scale ship noise measurement and estimation techniques".

6. RECOMMENDATIONS

The 30th Specialist Committee on Cavitation and Noise recommends adopting the following guidelines:

- ITTC Guideline 7.5-02-03-03.6: Podded Propulsor Model Scale Cavitation Test
- ITTC guideline 7.5-02-03-03.9: Model-scale Propeller Cavitation Noise Measurements
- ITTC Guideline 7.5-04-04-01: Underwater Noise from Ships, Full Scale Measurements.

We also recommend adopting the following procedures:

- ITTC Procedure 7.5-02-03-03.1: Model-Scale Cavitation Test.
- ITTC Procedure 7.5-02-03-03.2: Visual Description and Measurements of Cavitation Events.
- ITTC Procedure 7.5-02-03-03.3: Cavitation Induced Pressure Fluctuations Model Scale Experiments.
- ITTC Procedure 7.5-02-03-03.4: Cavitation Induced Pressure Fluctuations: Numerical Prediction Methods.
- ITTC Procedure 7.5-02-03-03.5: Model Experiments including Numerical Simulation Guidance for Propeller and Rudder Cavitation Erosion
- ITTC Procedure 7.5-02-03-03.8: Modelling the behaviour of Cavitation in Waterjets.

The recommendations for future work are:

1. Continue to organize of the Round Robin Test: collect and analyze data. Summarize the main trends.
2. Investigate the possibility of launching a benchmark on CFD. Topics could be noise, wake simulation, Tip Vortex Cavitation (TVC), cavitation inception, "classical" CFD with the Nawigator XXI (study the possibility to liaise with Wageningen Workshop on CFD).
3. Review of wake's evaluation in the state of the art.
4. Review URN measurements in ice conditions with a particular focus on accuracy
5. Continue monitoring the accuracy of URN measurements at model scale including the calibration, reverberation, and new methodologies (comprising instrumentations) for the measurement of propeller noise in tunnel facilities.
6. Monitor the progress of signal processing techniques in the two domains (cavitation, noise) and notably the use of data-machine learning and AI approaches (data-driven simulations).
7. Review of methods for cavitation noise mitigation, including bubble injection below the hull and its effect on URN.
8. Provide recommendation about cavitation testing of renewable energy devices (vertical or horizontal axis tidal turbines, etc.) and examine the possibility of a guideline.
9. Monitoring of energy saving devices for efficiency improvement and the way to

manage both objectives (energy saving efficiency and low noise emission).

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