EXPERIMENTAL INVESTIGATION OF CAVITATION-INDUCED ACOUSTIC NOISE FROM MARINE PROPELLERS

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ABSTRACT
Ship-induced acoustic noise can be treated as a measure of environmental impact of marine transportation industry, where, if present, cavitation is often the dominant noise source. Quantitative prediction of emitted noise levels requires detailed characterization of cavitation regimes associated with operation of marine propellers. We conducted an experimental campaign in a pressurized cavitation tunnel, following the experimental standards of the International Towing Tank Conference (ITTC). The experiments were designed to reproduce various cavitation regimes that are expected to occur during operation of a typical four-bladed propeller of a tanker ship. The measurements were conducted under steady inflow conditions, which eliminated the effects of the hull wake and shaft inclination in order to provide a first set of simplified cases for validation of numerical methodologies, before moving to more complex conditions. We obtained stroboscopic photographic images of the cavitation event, measurements of propeller loads, and high-resolution acoustic pressure levels across a broad frequency spectrum. The distinct regimes of bubble cavitation, sheet cavitation, and tip vortex cavitation were created experimentally in varying combinations, along with a reference case of cavitation suppression. For each considered cavitation regime, we identified the corresponding dominant frequencies and levels of the acoustic noise. The experiments will validate the propeller cavitation noise model that is used to guide ship hybrid electric propulsion system design and operation control to reduce ship induced ocean noise.

INTRODUCTION
Acoustic noise is a critical component of the overall pollution emitted from marine vessels, where the dominant noise source...
is often cavitation induced by the ship propellers [1], [2]. Attention to this anthropogenic noise source has grown following recent understanding of its chronic impacts on marine fauna [3], [4], and ship noise emission regulations are expected to become wide spread in the near future. The ability to predict noise production from marine vessels is of primary importance for developing intelligent mitigation approaches, including operational strategies and propeller designs. While semi-empirical noise prediction models relying primarily on vessel velocity have existed since the WWII era, these models neglect the significant influence of varied propeller cavitation types, limiting their applicability and validity. It is therefore necessary to investigate the influence of cavitation characteristics on propeller noise, as well as the predictive value of related high-level hydrodynamic parameters.

The present paper outlines an experimental campaign conducted on a scale model propeller in a cavitation tunnel. The present results intend to serve as a validating benchmark for numerical simulations. Uniform inflow conditions were used in place of a more conventional simulated hull wake in order to simplify the corresponding numerical problem. A range of operating parameters was examined to produce a representative range of cavitation phenomena. The cavitation types observed in the current study are tip vortex cavitation, sheet cavitation, pressure-side cavitation and bubble cavitation. The corresponding cavitation patterns are shown schematically in Fig 1. Control of the cavitation number and thrust coefficient allowed noise contributions from these individual types of cavitation to be studied both in isolation and in various combinations. Relations between the observed cavitation structures and the corresponding acoustic spectra were analyzed in order to develop semi-empirical models of cavitation induced noise.

**EXPERIMENTAL SYSTEMS AND TECHNIQUES**

Cavitation tunnel tests were carried out at the University of Genoa cavitation tunnel. The closed circuit water tunnel had a square test section of 0.57 m x 0.57m cross-section with a length of 2.2 m, as shown in Figs. 2 and 3. Water quality was monitored by routine measurements of the amount of dissolved oxygen. A dissolved oxygen content level of approximately 4.5 ppm was maintained in order to correctly simulate cavitation while avoiding possible noise absorption by free bubbles. Propeller thrust, torque, and rotation speed were measured with

![FIGURE 1: SCHEMATIC OF PROPELLER CAVITATION REGIMES.](image1)

![FIGURE 2: SCHEMATIC OF THE CAVITATION TUNNEL. LABELLED UNITS IN (MM).](image2)

![FIGURE 3: LEFT: LONGITUDINAL VIEW OF THE TEST SECTION. RIGHT: TRANSVERSAL VIEW. H1, H2 – HYDROPHONE LOCATIONS. LABELLED UNITS IN (MM).](image3)
a dynamometer. The corrections of Wood and Harris [5] were used to correct the measurements to account for tunnel effects. Stroboscopic images of the propeller cavitation were captured by three Allied Vision Tech Marlin F145B2 Firewire cameras, with a resolution of 1392 x 1040 pixels. Lighting was provided by two Movistrob type 900 lamps driven by a stroboscope Movistrob type 900-s.

Noise measurements were recorded by means of two miniaturized hydrophones, namely one Bruel & Kjaer type 8103 and one Reson TC4013, both driven by individual Bruel & Kjaer type 2635 charge amplifiers. Each acoustic acquisition consisted of 2^{11} samples, acquired with a sampling frequency of 200 kHz. Hydrophone positions within the cavitation tunnel are shown in Fig. 3. One hydrophone, referred to here as ‘H1’, was a Bruel & Kjaer type 8103 and was positioned outside the tunnel test section in a plexiglass tank below the propeller. This tank is completely filled with water and separated from the flow. The second hydrophone, referred to here as ‘H2’, is placed inside the tunnel, protruding from a fin. Acoustics measurements of hydrophone H2 only are presented hereafter for brevity.

The experiments were performed on a controllable pitch propeller (CPP) at two pitch settings, referred to hereafter as the design pitch and the reduced pitch. The main propeller characteristics are reported in Tab. 1. Uniform inflow conditions were implemented for all present cases.

**TABLE 1: PROPELLER CHARACTERISTICS.**

<table>
<thead>
<tr>
<th>Type</th>
<th>CPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Left</td>
</tr>
<tr>
<td>Model diameter (m)</td>
<td>0.24</td>
</tr>
<tr>
<td>Design pitch (P/D)_{0.7R}</td>
<td>0.876</td>
</tr>
<tr>
<td>Reduced pitch (P/D)_{0.7R}</td>
<td>0.521</td>
</tr>
</tbody>
</table>

The advance ratio and the cavitation index were varied to achieve a range of cavitation phenomena as listed in Tab 2. Definitions of the parameters used are provided in the nomenclature. Several noise measurements were carried out for each operation condition after stopping and restarting the cavitation tunnel to check repeatability of the results. Further, a sensitivity study was performed by inducing small percentage variations to functioning parameters to check measurement uncertainty.

The propeller cavitation patterns that developed for each operating condition are broadly categorized in Tab. 2. Further descriptions and visual observations of the cavitation phenomena are provided in the following section.

Post-processing procedures for the radiated noise primarily followed the ITTC guidelines for model scale noise measurements [6]. In addition, the average power spectral density, \( G(f) \) in Pa^2/Hz, was computed from each sound pressure signal \( P(t) \) using Welch’s method [7] of averaging modified spectrograms. The sound pressure power spectral density level \( L_P \) is then given by:

\[
L_P(f) = 10 \log_{10} \left( \frac{G(f)}{P_\text{ref}^2} \right) \ [\text{dB re} \ 1 \mu\text{Pa}^2/\text{Hz}]
\]

Results are presented in terms of the non-dimensional pressure coefficient \( K_p \) defined as:

\[
L_{K_p} = 20 \log_{10} \left( \frac{K_p}{10^{-6}} \right)
\]

The net sound pressure levels were computed by subtracting background noise from total noise as:

\[
L_{PB} = 10 \log_{10} \left( 10^{L_{PTOT}/10} - 10^{L_{BG}/10} \right)
\]

Further definitions and methodologies were unvaried from the ITTC guidelines.

**CAVITATION IMAGING**

Stroboscopic images of selected operating conditions with the design pitch are provided in Fig. 4 and Fig. 5, showing the suction side and pressure side of a single blade, respectively, at the 90° and 270° positions. Periodic unsteadiness in cavitation patterns throughout a rotation cycle was not visualized.

Stable tip vortex cavitation occurred in isolation in cases C1 (not shown) and C2. Condition C2, with a lesser cavitation number, showed a thicker vortex cavity. Condition C3, with a further decrease in cavitation number, exhibited small bubble-type cavitation and in some cases, narrow streak cavitation, in addition to a further thickened tip vortex.

**TABLE 2: EXPERIMENTAL CONDITIONS.**

<table>
<thead>
<tr>
<th>Name</th>
<th>((P/D)_{0.7R})</th>
<th>(J)</th>
<th>(\sigma_N)</th>
<th>(N) (rps)</th>
<th>(K_r)</th>
<th>10(K_p)</th>
<th>Observed Cavitation Type(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.87</td>
<td>0.516</td>
<td>2.9</td>
<td>25</td>
<td>0.205</td>
<td>0.293</td>
<td>Tip vortex</td>
</tr>
<tr>
<td>C2</td>
<td>0.87</td>
<td>0.516</td>
<td>2.3</td>
<td>25</td>
<td>0.205</td>
<td>0.293</td>
<td>Tip vortex</td>
</tr>
<tr>
<td>C3</td>
<td>0.87</td>
<td>0.516</td>
<td>1.4</td>
<td>25</td>
<td>0.205</td>
<td>0.293</td>
<td>Bubble, streak, tip vortex, suction side sheet</td>
</tr>
<tr>
<td>C4</td>
<td>0.87</td>
<td>0.769</td>
<td>2.3</td>
<td>25</td>
<td>0.090</td>
<td>0.172</td>
<td>Pressure side leading edge</td>
</tr>
<tr>
<td>C5</td>
<td>0.87</td>
<td>0.345</td>
<td>2.3</td>
<td>25</td>
<td>0.270</td>
<td>0.350</td>
<td>Tip vortex, suction side sheet</td>
</tr>
<tr>
<td>C1b</td>
<td>0.521</td>
<td>0.404</td>
<td>2.6</td>
<td>30</td>
<td>0.095</td>
<td>0.125</td>
<td>Pressure side leading edge</td>
</tr>
<tr>
<td>C2b</td>
<td>0.521</td>
<td>0.404</td>
<td>2.3</td>
<td>30</td>
<td>0.095</td>
<td>0.125</td>
<td>Pressure side leading edge</td>
</tr>
<tr>
<td>C3b</td>
<td>0.521</td>
<td>0.404</td>
<td>1.4</td>
<td>30</td>
<td>0.095</td>
<td>0.125</td>
<td>Pressure side leading edge</td>
</tr>
<tr>
<td>C4b</td>
<td>0.521</td>
<td>0.500</td>
<td>2.3</td>
<td>30</td>
<td>0.050</td>
<td>0.095</td>
<td>Pressure side leading edge</td>
</tr>
<tr>
<td>C5b</td>
<td>0.521</td>
<td>0.345</td>
<td>2.3</td>
<td>30</td>
<td>0.120</td>
<td>0.140</td>
<td>None</td>
</tr>
</tbody>
</table>
Maintaining the same cavitation number as condition C2, the advance ratio for condition C4 was increased to induce cavitation on the pressure side, which developed on the leading edge from $r/R\sim0.5$ outward to the tip. A tip vortex cavity was not present. In contrast, the advance ratio for condition C5 was reduced to an extent that a suction side sheet cavitation and a developed tip vortex were present.

Not shown in the single blade views are the equivalent operating cases at the reduced pitch, as labelled C1b through C5b in Tab. 2. This off-design condition corresponded to lower effective angles of attack than the design pitch cases. As a result, conditions C1b, C2b, C3b, and C4b developed leading edge cavitation on the pressure side of the blade, from $r/R\sim0.6$ outward to the tip. The views of the pressure side of the blade corresponding to cases C2 and C2b are shown in Fig. 6, highlighting the presence of pressure side cavitation in the reduced pitch condition. Pressure side cavitation was more developed in conditions C3b and C4b, showing a rather large vortex from sheet face; however, the extent of this cavity was less than many of the vortices observed in the design pitch cases (on the suction side). Condition C5b had no visible cavitation. Its noise signature, which was slightly above the baseline non-cavitating condition, indicates it was near cavitation inception.

Trailing tip vortices were observed in the design pitch cases, excepting C4, and they persisted for several propeller diameters downstream before collapsing. The pressure side leading edge cavities of the reduced pitch cases and case C4 collapsed on the propeller blades or shortly downstream.

**FIGURE 4:** STROBOSCOPIC IMAGES OF CAVITATION EVENTS DURING CONDITIONS C2, C3, C4, C5. THE SUCTION SIDE OF THE BLADE IS SHOWN AT 90°, VIEWED FROM ABOVE.

**FIGURE 5:** STROBOSCOPIC IMAGES OF CAVITATION EVENTS DURING CONDITIONS C2, C3, C4, C5. THE PRESSURE SIDE OF THE BLADE IS SHOWN AT 270°, VIEWED FROM ABOVE.

**FIGURE 6:** COMPARISON OF STROBOSCOPIC IMAGES FROM COMPARABLE DESIGN PITCH (C2) AND REDUCED PITCH (C2B) CASES, SHOWING FULL PROPELLER (LEFT) AND PRESSURE SIDE SINGLE BLADE (RIGHT) VIEWS.

**ACOUSTIC MEASUREMENTS**

Acoustic measurements corresponding to representative conditions C1, C2, and C3 tested in non-cavitating regimes are provided in Fig. 7, and compared against background tunnel noise. The noise emitted by the non-cavitating propeller was primarily background noise, with exceptions at the tone of the blade rate and, occasionally, its first multiple.

Acoustic spectra for cavitating propeller cases with the design pitch are provided in Fig. 8. Total noise spectra have been corrected for background noise, according to ITTC guidelines, in order to isolate propeller noise. Portions of the dataset that
have a signal-to-background noise ratio less than 3 dB have been omitted. In some cases, primarily those corresponding only to tip vortex cavitation, this omission included a significant portion of the low-frequency range, indicating minimal noise generation by the propeller sources in this range.

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FIGURE 7: NON-CAVITATING PROPELLER NOISE FOR CONDITIONS C1, C2, C3; AND BACKGROUND TUNNEL NOISE.

Acoustic spectra for the propeller operating under the reduced pitch are provided in Fig. 9. Qualitatively similar acoustic patterns were seen for each case, particularly in the frequency range above 1000 Hz. This result is expected, considering that pressure side cavitation was characteristic of each case C1b through C4b. The amplitude of each spectrum differed between cases, roughly corresponding to the net cavity size observed in the stroboscopic images.

Large portions of the data in the low-frequency range were omitted due to low signal-to-noise ratio, indicating that the noise in this range was primarily the background noise.

Figure 10 presents a comparison between design pitch and reduced pitch cases. Similar patterns are seen between all cases in the tonal frequency range. However, in the design pitch cases, a notable hump was present in the spectra between 200 Hz and 800 Hz. This increased noise level is characteristic of tip vortex cavitation and it was absent in the reduced pitch cases [11]. At frequencies above 1000 Hz, the general trend of logarithmic decay was observed for each case, excepting condition C3. While the acoustic data trends were preserved between the design and reduced pitch cases, the reduced pitch experiments showed increases in sound pressure levels up to 20 dB greater their comparable design pitch condition. This result is counterintuitive, considering that the reduced pitch tests were performed at lower freestream velocities, thrust coefficients, and torque coefficients. However, pressure side cavitation is expected to result in significantly higher levels of noise than comparable suction side cavitation and is less likely to occur during design operating conditions [10]. Indeed, the higher noise levels measured for the reduced pitch cases were accompanied by pressure side cavitation in the stroboscopic images.

The conditions that developed vortex and sheet cavitation showed an approximate 4 – 4.5 dB/octave decay at frequencies above ~250 Hz. The results lay within the range predicted more recently by [10] and suggest that sound pressures in this range can be modelled by a simple equation fit. The bubble cavitation observed at condition C3 represented an exception, where the sound pressure at high frequencies decayed at lower rate and with no clear trend.

FIGURE 9: NET POWER SPECTRUM LEVELS FROM CAVITATING EXPERIMENTS OPERATING AT THE REDUCED PITCH, AS MEASURED BY HYDROPHONE H2. A 4DB/OCTAVE DECAY IS SHOWN FOR REFERENCE.

FIGURE 8: NET POWER SPECTRUM LEVELS FROM CAVITATING EXPERIMENTS OPERATING AT THE DESIGN PITCH, AS MEASURED BY HYDROPHONE H2. A 4DB/OCTAVE DECAY IS SHOWN FOR REFERENCE.
This result highlights the need for intelligent operating strategies to reduce anthropogenic marine noise. Rudimentary control strategies that assume linear ship velocity-to-noise relations should be avoided. For example, in the case of a decelerating ship with a controllable pitch propeller, keeping the engine speed fixed while adjusting the propeller pitch would result in excessive noise levels [12]. Rather, a more appropriate speed-reduction strategy would be to maintain the effective angle of attack of the propeller blades close to the design values in order to reduce cavitation, especially on the pressure side of the blades.

CONCLUSIONS

Scaled cavitating propeller experiments were performed, providing insight into underlying relations between cavitation events and their noise signatures. The observed data trends suggest that only a few high-level parameters, such as cavitation number, thrust coefficient, advance ratio, and pitch angle, could be sufficient in defining appropriate, reduced-order noise estimation tools. The present results suggest that logarithmic decay models can be effective for predicting acoustic noise spectra from tip vortex, sheet, and pressure side cavitation, but may be ineffective for the case of bubble cavitation.

In the case of reduced-pitch propeller operation, the acoustic effects of pressure-side cavitation were observed to dominate the effects of the reduction of cavitation number and thrust coefficient, resulting in higher levels of noise. This finding confirms the assertion that linear ship speed-noise models are insufficient for predicting propeller cavitation noise.

The stroboscopic images of the cavitation events and the concurrent acoustic measurements provide a benchmark for development of numerical and semi-empirical models of cavitation-induced noise. These models will allow cavitation noise, the primary source of ship-induced noise, to be effectively considered in designing marine propulsion systems, choosing propellers, and operating marine vessels.

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