Cavitation on small craft propellers and its contribution to underwater radiated noise

Tom A. Smith[1], Andrea Grech La Rosa[1], Solomon S. McMorran[2], Giles Piggott[3], and João A. N. Gaivota [4]

[1]Department of Mechanical Engineering, University College London, London, WC1E 6BT
[2]Royal Canadian Navy
[3]Royal Navy
[4]Portuguese Navy

Tom Smith, Department of Mechanical Engineering, University College London, Gower Street, London, WC1E 6BT, tom.smith.17@ucl.ac.uk

Abstract: *Cavitation is a major contributor to underwater radiated noise (URN) from commercial ships but less is known about the dynamics, inception speed, and contribution of cavitation to URN for small vessels. Small vessels often use propellers located very close to the free surface and which turn at high speeds. This means that the cavitation dynamics are likely to be different from those on larger ships. Additionally, many small vessels are powered by internal combustion outboard engines, which typically expel exhaust gases through the hub, leading to a bubbly hub vortex. In this work, acoustic data from small boat trials are presented alongside underwater camera footage to show how cavitation develops on small high speed propellers and how it contributes to the acoustic signature. The results show that the cavitation inception speeds are typically 5-6 knots, and this is accompanied by a sharp rise in noise across a broad frequency range. Visual footage shows that tip vortex cavitation (TVC) dominates at low speeds. Results are also presented that provide insights into how the material state of the propeller can influence the cavitation dynamics. Whilst rough and fouled propellers might be assumed to cavitate earlier and hence be louder than their smooth counterparts, it is shown here that this is not always the case. When tip vortex cavitation dominates, small amounts of roughness can actually reduce URN levels by disrupting the formation of the tip vortices.*

Keywords: *propeller cavitation, underwater radiated noise, experimental trials*

1. INTRODUCTION

Propeller cavitation is a significant contributor to radiated noise from ships and can also lead to efficiency losses, vibration, and erosion [1]. Over past decades there have been a multitude of studies on ship propeller cavitation, and this work has led to significant design improvements. Despite this, cavitation remains a problem on vessels of all sizes, and is extremely difficult to avoid at higher speeds [2]. For larger vessels, it typically dominates the acoustic signature at higher speeds, producing noise across a wide frequency range.

Recent research has highlighted the acoustical importance of small boats, particularly in shallow and coastal waters where they can dominate the soundscape [3, 4]. This has prompted increased interest in quantifying levels of URN from small craft and understanding the underlying sources [5, 6, 7]. These studies show that the relationship between speed and noise levels is less clear than it is for larger vessels, and this may partly be due to cavitation not always being worse at higher speeds [8]. Few studies have discussed cavitation on small craft in any detail, and visual footage from field trials is rare. As a result, cavitation inception speeds are not readily available, and the contribution of cavitation noise to the overall noise levels is not known for small vessels. In many cases, propellers are "off-the-shelf" and many have not undergone testing to determine their cavitation performance. This, together with the higher rotational speeds and their proximity to the free surface make it likely that the cavitation performance will be different for small high-speed propellers than it is for a typical large ship propeller.

This paper presents recent experimental research carried out into the acoustical impact of propeller cavitation on small boats powered by internal combustion engine (ICE) outboard motors. Underwater noise data are presented for two vessels: a 5 m and a 6 m rigid inflatable boat (RIB) alongside camera footage for the 5 m RIB. The results consider three areas: the role of exhaust gases, the cavitation inception speed and the change in signature due to the onset of cavitation, and the role of the propeller surface quality.

2. METHODS

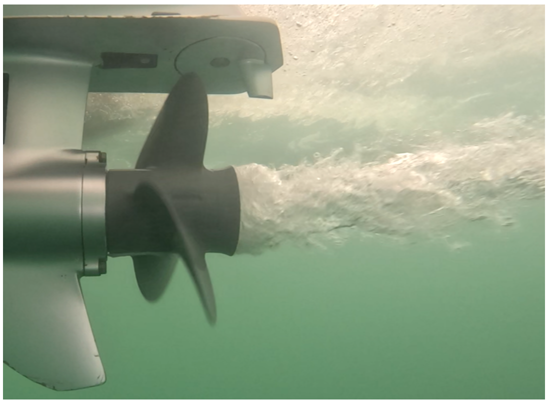
The results presented in this work pertain to trials carried out in July 2024 off the south coast of England. The weather conditions were calm and commensurate with sea state 2. Two RIBs were used and their principal particulars are shown in Table 1.

A detailed description of the trial setup is given in [9] and so only a brief description is given here. Acoustic measurements were made with two RS Aqua/Turbulent Research acoustic recorders sampling at 384 kHz. These were located at a horizontal distance of 20 m from the closest point of approach and 3 and 5 m above the seabed, which consisted of sand and mud. As discussed in [9], this is closer than is recommended by ISO 17208 and was motivated by the desire to improve the signal-to-noise ratio, particularly as the focus of this study is to try to understand the contributions of particular types of cavitation to the acoustic signature. Camera footage was obtained using a GoPro Hero 11 recording at 240 frames per second. This was mounted in a custom-made faired frame. Trials were carried out using double runs, with three double runs per speed. Additional trials were carried out where the vessel speed was increased incrementally to determine the cavitation inception speed using the camera.

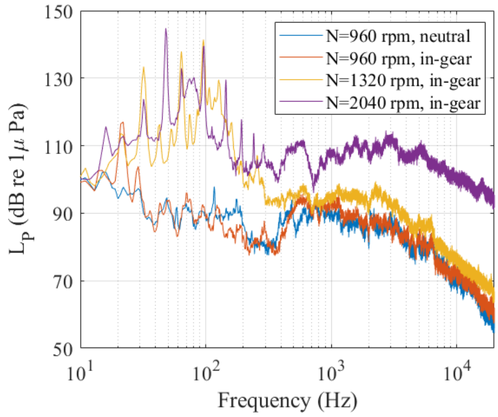
The data are analysed using the approach set out in [9] and uncertainty analysis is presented in [9, 10]. Source levels are computed from the received levels using the Seabed Critical Angle method [11].

	5 m RIB	6 m RIB
Length overall (m)	5.0	5.9
Beam (m)	2.2	2.5
Max engine power (kW)	37	104
Number of cylinders	3	4
Gearbox ratio, g	2.1	2.6
Number of blades, z	3	3
Propeller diameter, D (m)	0.28	0.36
Pitch-diameter ratio, P/D	1.17	not known

Table 1: Vessel particulars for the two boats



(a)



(b)

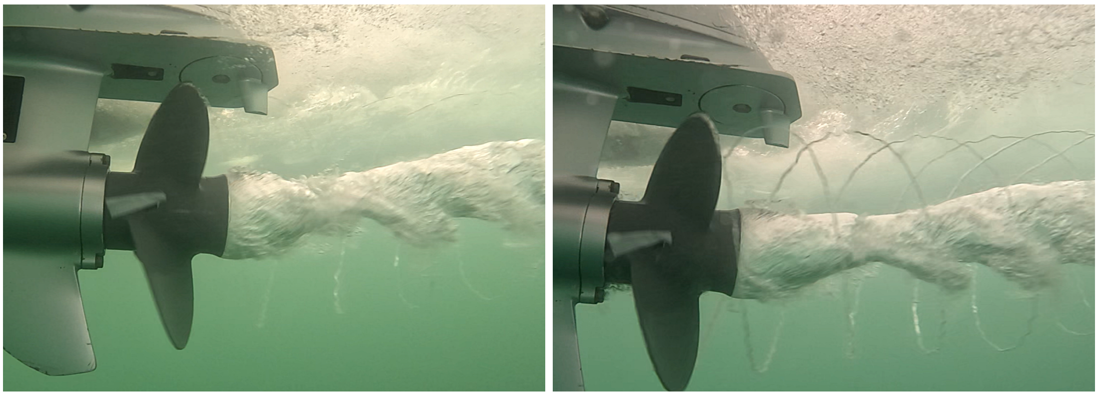
Figure 1: (a) hub gases being expelled through the hub of the 5 m RIB at 4 knots. (b) narrow-band spectra for the vessel moored up with the engine running at different speeds.

3. RESULTS

3.1. EXHAUST GASES

ICE outboard motors typically have two exhausts: one above the waterline and one in the propeller hub. When idling or at very low speeds, gases are expelled through a port above the waterline. As the speed increases (usually at around 3-4 knots), the increased pressure in the engine and the reduced pressure in the hub vortex results in the gases being expelled through the hub. This is shown in Figure 1(a) which is for the 5 m RIB travelling at 4 knots.

This has two important consequences for underwater noise. Firstly, it results in the hub being relatively large as a proportion of the overall propeller diameter. Thus, for a given diameter, there is less area providing thrust which increases the load per unit area and hence the propensity for the propeller to cavitate. Secondly, the expulsion of gas into the low pressure hub vortex core creates noise. To determine how this contributes to the acoustic signature, trials have been carried out with the vessel tied alongside and doing a bollard pull. This has been done to eliminate noise from spray and other hydrodynamic sources. The engine was run at a series of different speeds and a hydrophone located 2 m away from the propeller recorded the sound. Narrowband spectra are shown in Figure 1(b) for the vessel when idling and at two higher engine



(a) *(b)*

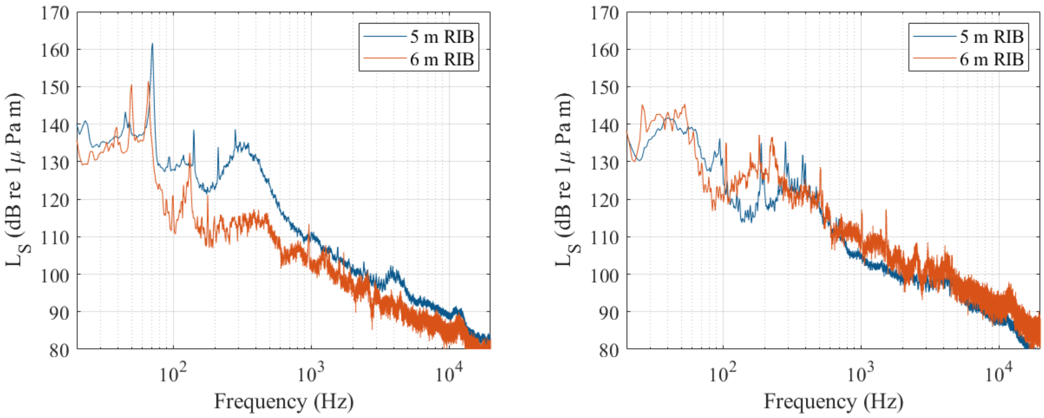
Figure 2: Tip vortex cavitation on the 5 m RIB at (a) 5 knots and (b) 6 knots.

speeds. When idling and not in gear, the noise levels are only very slightly above background noise. When idling but in gear, tonal components at the engine firing rate and propeller rate are observed but no other significant changes are observed. At 1320 RPM, the exhaust gases are expelled through the hub but no cavitation is observed. In addition to an increase in tonal components at the engine and propeller rates, there is a pronounced low-frequency broadband hump from 10 to 300 Hz. At 2040 RPM, the low frequency noise levels are similar, but there is a significant increase in broadband levels at mid and high frequencies. The camera footage shows that cavitation is present at this speed and so this noise is likely dominated by cavitation collapse. From this, we can deduce that the exhaust gases result in a low frequency broadband hump in the acoustic spectrum.

3.2. CAVITATION INCEPTION AND TIP VORTEX CAVITATION

No consistent cavitation was observed on either vessel below 5 knots. However, occasional bubble collapse signals were measured at 4 knots. Analysis of the camera footage showed that this is due to pre-existing bubbles in the water being drawn close to the propeller tip where they expand and then collapse. Further details can be found in [9].

TVC emerges on the propeller on the 5 m RIB consistently at 5 knots. At 6 knots, fully developed TVC is observed, with cavitating tip vortices propagating several propeller diameters downstream before they break up and collapse. Images of the cavitation pattern at 5 and 6 knots are shown in Figure 2. The onset and development of cavitation on the 6 m RIB follows a similar pattern, but this occurs at a slightly higher speed, with TVC first appearing at 6 knots but not fully developing until around 8 knots. This is partly because the 6 m RIB uses a larger propeller that operates at a lower speed. At 5 knots, the cavitation number calculated using the propeller rotation rate is $\sigma_n = 0.76$ for the 5 m RIB and $\sigma_n = 1.32$ for the 6 m RIB. By 6 knots, this has reduced to $\sigma_n = 0.90$ for the 6 m RIB, and so cavitation first occurs at a similar cavitation number for the two vessels. Narrowband spectra for the two vessels are shown in Figure 3 at 6 and 10 knots. For the 5 m RIB at 6 knots, the blade rate is very pronounced and there is a broadband hump centred around 400 Hz. This is characteristic of TVC noise [12]. This is far less prominent for the 6 m RIB due to the later emergence of cavitation. The increase in high frequency noise on the 6 m RIB going from 6 to 10 knots coincides with the increasing levels of cavitation. At 10 knots, a broadband hump is visible for both vessels but is far less prominent



(a) *(b)*

Figure 3: Narrowband source levels for the two vessels at (a) 6 knots and (b) 10 knots

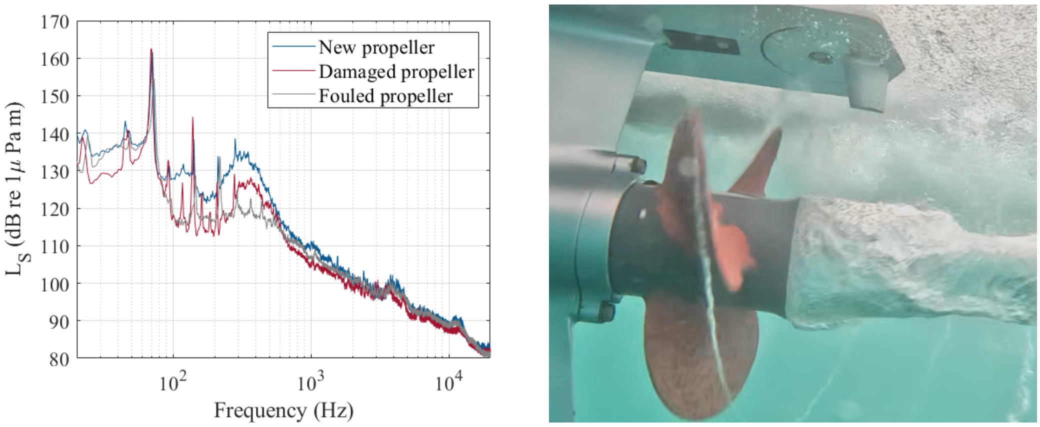
and the broadband noise levels are actually lower for the 5 m RIB at 10 knots than at 6 knots. It was not possible to obtain good camera footage at 10 knots due to the large number of bubbles being entrained in the flow. It may therefore be that these bubbles are attenuating some of the noise and this may partly explain the lower noise levels. It may also be that higher turbulence levels disrupt the formation of the tip vortices. Changes in propeller loading also occur over this speed range, as noted in [9]. Further research is needed to better understand the mechanisms here, as the results show that speeding up can be beneficial from a noise perspective, which is generally not the case for larger vessels.

3.3. THE ROLE OF DAMAGE AND ROUGHNESS

It might reasonably be assumed that a rough or damaged propeller would exhibit cavitation at a lower speed than a clean propeller and that the levels of cavitation at a given speed would be worse. A rough propeller will be less efficient and must therefore run faster to achieve the same vessel speed. Roughness elements can also act as nucleation sites by stabilising gas volumes at the propeller surface. The pressure fluctuations due to turbulence created by roughness may also lead to the local pressure dropping below the threshold pressure earlier.

However when TVC is present, studies have shown that roughness at the tip can effectively reduce TVC by modifying the roll-up process and leading to a weaker vortex strength [13, 14]. To provide further insights into how roughness and damage/wear affects propeller noise levels, trials have been conducted at 6 and 10 knots using a clean, slightly damaged, and an artificially roughened propeller. This was roughened by applying 1-2 mm elements randomly across the blade surfaces. The details of the material state of these propellers are given in [10] and photographs are shown in Figure 4. The narrowband source levels are shown in Figure 5 and this confirms the findings of the aforementioned studies. Even a very moderate level of surface wear or roughness can be effective at alleviating TVC. The propeller still cavitates at 6 knots, as shown in Figure 5(b), but it is far more fragmented and does not extend as far downstream. As a result, the noise due to collapse (typically high frequency) is the same but the lower frequency noise associated with the oscillating cavity volumes is significantly reduced. Further research is needed to understand the minimum levels of roughness required to achieve this and to determine whether this effect is observed over a wider range of operating conditions.

Figure 4: The clean (left), damaged (centre), and artificially roughened (right) propellers.



(a) *(b)*

Figure 5: (a) Narrowband spectra for the 5 m RIB at 6 knots with the three propellers. (b) Cavitation on the roughened propeller at 6 knots. Adapted from [10].

4. CONCLUSIONS

This work has presented an overview of recent research carried out into propeller cavitation on small craft. It has been shown that cavitation inception speeds can be as low as 5 knots in calm water, suggesting that cavitation is likely to be present on these vessels at most operating speeds. Tip vortex cavitation has been shown to appear first, accompanied by a significant rise in noise at both low and high frequencies. However, this noise may not always persist and has been shown to sometimes decrease as the vessel speed increases. Furthermore, trials have shown that a rough or damaged propeller can actually produce less noise. Based on previous studies [14], this is because the roughness (or roughness elements associated with tip damage) alter the vortex roll-up process and reduces its strength.

Further research is planned to investigate cavitation levels at higher speeds and to further investigate ways of mitigating tip vortex cavitation without reducing the propeller efficiency.

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