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A comparative study of underwater radiated noise from electric and conventional boats

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ABSTRACT:
Electric propulsion systems for marine vessels are becoming more common, particularly on small craft. While often assumed to be much quieter than their combustion counterparts, there are only a few studies that quantify underwater radiated noise (URN) levels, and the results paint a complex picture. In this work, the URN characteristics of two vessels are compared. The vessels are of the same design, but one is powered by a conventional outboard engine whereas the other has an electric outboard. The results show that the broadband source levels for the electric vessel are lower across the entire speed range tested (4–20 kn). The largest benefit is at low speed where cavitation is minimal. At 4 kn, the broadband source level for the electric vessel is 43 dB lower than for the conventional vessel. At higher speeds, cavitation becomes increasingly important, but the broadband source level remains lower for the electric boat even once cavitation is present. Furthermore, the high-frequency noise from the motor is found to be lower than in other studies, highlighting that not all electric propulsion systems should be treated equally from a URN perspective.
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I. INTRODUCTION

Global efforts to reduce carbon emissions from maritime transport are leading to the development and installation of alternative propulsion systems. As part of this, electric propulsion systems are being developed for a range of platforms, from small boats to ferries. Recent innovations in battery energy density and charging infrastructure are enabling longer operational ranges, making electrification a practical option for more types of vessels (Moon *et al.*, 2024), particularly smaller vessels due to their reduced power and endurance requirements. As a result, several different electric propulsion systems, particularly outboard systems, are now available and electric propulsion vessels are becoming increasingly common in marine environments.

In addition to carbon emissions, underwater radiated noise (URN) from vessels is receiving considerable attention due to concerns over its impacts on marine life (Chou *et al.*, 2021; Duarte *et al.*, 2021; Ferrier-Pagès *et al.*, 2021; Slabbekoorn *et al.*, 2010). An extensive body of research has identified that marine mammals are of particular concern due to their reliance on hearing as a primary sense for foraging, navigating, detecting predators, and communicating (Richardson *et al.*, 2013). URN from vessels has been documented to negatively impact marine mammals in several ways, including masking biologically important acoustic cues (Pine *et al.*, 2018), and altering behavior (Aguilar Soto *et al.*, 2006; Frankish *et al.*, 2023; Sprogis *et al.*, 2020; Wisniewska *et al.*, 2018), which could result in energetic consequences for species over time. Research has also identified that many fish species can be negatively impacted by anthropogenic noise (see, e.g., Simpson *et al.*, 2016; Stanley *et al.*, 2017). However, although much attention has been paid to the effects on marine life from exposure to underwater noise from large commercial vessels with combustion engines (Erbe *et al.*, 2019), only a few studies have measured the underwater noise produced by electric propulsion systems (Andersson *et al.*, 2024; Gaggero *et al.*, 2024; Parsons *et al.*, 2020), which has limited our ability to assess impacts on noise sensitive species.

Small outboard-powered vessels are extremely common across the globe and operate in a wide variety of environments: from built-up urban waterways to remote and environmentally sensitive waters. The global market for the outboard engines which power many small craft was estimated to be worth around $11.2 billion in 2024, and is predicted to grow over the next decade (https://www.precedenceresearch.com/outboard-engines-market). Small boats may not produce source levels as large as some ships, but they should not be discounted as broadband source levels in excess of 170 dB re 1 μPa m have been reported for vessels less than 10 m in length (Smith *et al.*, 2024b). Furthermore, studies have now shown that small craft can actually dominate the soundscape in shallow coastal

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environments (Hermannsen *et al.*, 2019), potentially altering the behavior or masking important biological cues of acoustically sensitive marine fauna inhabiting these environments (Duarte *et al.*, 2021; Erbe *et al.*, 2019). Small boat noise has been shown to have negative consequences for some fish in coral reef environments (Nedelec *et al.*, 2017), again highlighting that these vessels should not be discounted as important acoustic sources. Indeed, one study showed that limiting motorboat noise could improve the success of fish reproduction in a coral reef environment (Nedelec *et al.*, 2022). Although a few studies have shown that some marine life can become acclimatized to the elevated noise levels from small boats (Harding *et al.*, 2018; Holmes *et al.*, 2017), the net impact on many marine ecosystems remains negative. Consequently, the growth in outboard-propelled vessels and the increase in electric options mean that more data are needed to understand the acoustical impact of small boats on the marine environment.

It is often assumed that a vessel powered by an electric propulsion system will be quieter than one powered by a combustion engine due to the absence of combustion processes that produce significant levels of low-frequency sound. This assumption was borne out in one study (Parsons *et al.*, 2020), which compared the URN levels from two 10 m solar-electric ferries with those from two 25 m conventionally powered ferries. The study found that low-frequency noise was significantly reduced in the case of the electric ferry and that this would likely be of considerable benefit to animals which primarily hear and communicate at lower frequencies (<500 Hz), such as *Mysticeti* cetaceans and gadoid fishes (Stanley *et al.*, 2017). However, (Andersson *et al.*, 2024) found that the overall acoustical impact of the diesel generators on a hybrid ferry was relatively small, and so switching to fully electric propulsion had little impact on the underwater noise levels. This was because the noise levels were dominated by propeller cavitation at the speeds considered. In the study of Parsons *et al.* (2020), the vessels were traveling at 2.6 $\mathrm{m\,s^{-1}}$ (5 kn). At this speed, significant levels of cavitation are unlikely and so engine noise will play a more significant role. Evidence also suggests that electric vessels may produce significant noise at higher frequencies, making them increasingly audible to species with good high-frequency hearing capabilities, such as pinnipeds and odontocete cetaceans (Southall *et al.*, 2019). This was highlighted in a recent study (Gaggero *et al.*, 2024), which assessed the underwater noise levels from an 8 m vessel powered by two electric outboard motors at 4 and 6 kn. Here, it was found that the power electronics produced significant high-frequency tonal sounds at 10, 20, and 40 kHz. These results indicate that the vessel propulsion architecture and operating conditions are important factors in determining the underwater noise produced by electric vessels, which is expected to vary significantly across vessel classes and routes.

Based on these limited measurement studies, two key things stand out that may prevent the acoustical benefits of electric propulsion from being realized. The first is the role of the propeller, because if propeller cavitation is present, it is likely that this will dominate the high-frequency part of the spectrum while also producing significant levels of low-frequency noise. The speed at which it first occurs is the cavitation inception speed and this can be as low as 5 kn on small craft (Smith *et al.*, 2025). This is lower than often assumed for larger vessels, although few studies report the actual inception speed. Arveson and Vendittis (2000) report an inception speed of 10 kn for a 173 m cargo ship. Once present, cavitation can quickly become the dominant noise source. For example, one of the outboard propellers tested by Smith *et al.* (2025) started to cavitate at 5 kn and by 6 kn the cavitation noise dominated both the low- and high-frequency parts of the spectrum. The acoustical contribution of cavitation depends on many factors, including the propeller geometry and rotation rate, loading, the material state of the propeller, and the hullform, which determines the flow field in which the propeller operates (Ross, 2013; Smith *et al.*, 2024a; van Terwisga *et al.*, 2021). As with propellers on larger vessels, recent studies have shown that tip vortex cavitation tends to occur first on small boat propellers (Smith *et al.*, 2025). For a propeller operating in a spatially varying wake field (e.g., behind a hull), tip vortex cavitation produces very broadband noise. In addition to tonal noise at the blade rate (and harmonics), a low-frequency broadband hump can occur (often at around 4–7 times the blade rate), which is associated with the breathing mode of the cavitating vortex (Bosschers, 2019; Pennings *et al.*, 2016). High-frequency broadband arises from the collapse of the cavities once the tip vortices start to breakup (Choi and Ceccio, 2007; Franc and Michel, 2006). Consequently, broad spectrum propeller cavitation may be the dominant audible noise source for a wide range of marine life. In such a case, reducing the engine noise via electric propulsion may not have any significant impact.

However, this is not always the case, and machinery noise can still be significant on small boats even at higher speeds (Smith *et al.*, 2024b). The importance of engine noise depends on several factors, including speed, propulsion architecture, engine and machinery mountings, and vessel running attitude (Smith *et al.*, 2024b). All of these things must be considered when assessing whether electrification of a vessel will bring an overall benefit in underwater noise.

The second component to consider is the potential for electric motors and power electronics to create significant levels of high-frequency tonal noise. These tones arise from the pulse width modulation (PWM) used to control the motor, and this was the source of the high-frequency tonal noise in the study of Gaggero *et al.* (2024). This high-frequency tonal noise produced by electric outboards may therefore be of concern for high-frequency hearing specialists, such as harbour porpoises (*Phocoena phocoena*), which have best hearing in the range of approximately 10 to 140 kHz (Kastelein *et al.*, 2017), and have been documented to elicit strong behavioral responses (Dyndo *et al.*, 2015; Wisniewska *et al.*, 2018) and be at an increased risk of auditory masking (Beedholm *et al.*, 2025) during exposure to the high-frequency signals produced by a vessel. PWM noise can originate from the rapid switching of voltages used to control motor speed and torque in electric propulsion systems. In the context of motor control, PWM modulates the duration of "on" and "off" cycles in the power supply to the motor, allowing precise control over motor performance. However, this switching generates high-frequency electromagnetic interference and acoustic noise (Hubert and Friedrich, 2002), which can propagate through the motor structure, mountings, and into the surrounding environment, including into the water (Borisov *et al.*, 2006). This phenomenon is not limited to a specific type of motor but is prevalent in both AC and DC systems using PWM-based motor drives. The magnitude of noise depends on motor design, switching frequency, and the type of PWM strategy employed. The transmission of PWM noise into water is influenced by factors, such as the physical location of the motor and power electronics within the vessel, the material and design of the mountings, and the proximity of components to the hull. Mitigation measures to reduce this noise do exist and include using optimized PWM switching frequencies that minimise harmonics in sensitive frequency ranges and incorporating electromagnetic interference filters in the drive circuits (Kalair *et al.*, 2017). Advanced techniques, such as sinusoidal PWM or space vector modulation, can further smooth the motor input and reduce acoustic and electrical noise (Nandhini and Sivaprakasam, 2022). However, such techniques are not widely employed, and only limited studies have quantified their impact on URN.

Because the aforementioned studies all consider different vessels, propulsion types, and operating profiles, it is difficult to make any broad conclusions on the acoustical impact of vessel electrification on marine fauna at present. This is further complicated by animals perceiving the loudness of the same vessel differently (see, e.g., Southall *et al.*, 2019), which may result in responses to vessel passages varying by species, requiring considerations of noise impacts on a species-by-species basis. A better understanding of the underwater noise from electric propulsion vessels is therefore needed, particularly in the context of small craft as their coastal usage substantially overlaps with the core habitats of many marine species, is a dominant contributor to the soundscapes (Hermannsen *et al.*, 2019; Wilson *et al.*, 2022), and is where growth in electric propulsion systems is expected to be significant over the next decade.

To this end, this work presents experimental results from a trial conducted on two small vessels: one fitted with a conventional IC outboard engine, and one fitted with an electric outboard. The two vessels are almost identical in terms of hullform and material construction, allowing for a direct comparison of the noise associated with the propulsion system. The vessels are assessed across a broad speed range from 4 to 20 kn, covering the displacement and planing regimens as well as with and without propeller cavitation. As well as providing comparative data on the noise levels, the study details the makeup of the signature and how this changes between the two propulsion types.

II. METHODS

A. Test vessels

The vessels used in the trial are denoted EB for the electric boat and ICEB for the internal combustion outboard engine boat. Both have the same principal dimensions and hullform design. They are planing catamarans assisted by a foil located at midships. The foil provides additional lift, enabling the vessel to plane more efficiently. The principal particulars along with details of the propulsion systems and propellers are given in Table I. The ICEB is powered by a 37 kW 4-stroke petrol outboard engine and the EB by a RAD 40 electric drive. An image of the ICEB is shown in Fig. 1. Both vessels were loaded in the same way, with 3 people onboard. The EB is heavier than than the ICEB by 70 kg, and this is due to the weight of the batteries. This is commensurate with 15% of the dry weight. The loading conditions have not been altered to account for this, and so the EB as tested is 70 kg heavier than the ICEB. This has been done because the batteries are an integral part of the system, and so this enables a fairer comparison between the two boats.

The propellers have the same diameters but are not of the same design. This is because the propellers on combustion outboard engines have larger hubs to accommodate the expulsion of the exhaust gases. This leads to a larger hub-diameter ratio for the propeller on the internal combustion engine.

B. Trial location and experimental setup

The trial was conducted on a lake with a length of 670 m and an average width of 120 m. The site was chosen because it was sheltered, and there was no other vessel traffic. This led to very low background noise levels compared to typical coastal sites where these vessels typically operate. This also removed any tidal or current effects, which change the propeller loading as well as creating low-frequency noise due to flow over the hydrophones. Typical ambient noise levels are shown in Fig. 2. The depth in the area of the trial averaged 11 m (varying between 10.0 and 11.5 m) and the substrate was soft mud, which helps to limit reflections. The weather conditions were calm throughout the trial period with a wind speed of less than 10 kn.

TABLE I. Vessel particulars.

		ICEB	EB
Length (waterline)	m	3.6	3.6
Beam	m	1.9	1.9
Dry weight	kg (excluding PAX)	460	530
Propulsion	—	4-stroke petrol	Electric
Installed power	kW	37	40
Gear ratio	—	2.33	1.55
Propeller blades (z)	—	3	3
Propeller diameter	m	0.33	0.33
Pitch-diameter ratio	—	1.28	0.9
Hub-diameter ratio	—	0.3	0.23

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FIG. 1. Image of the ICEB. Photograph taken by the authors.

Acoustic measurements were made using 2 RS Aqua/ Turbulent Research Porpoise recorders sampling at 192 kHz. These were located at a horizontal distance of 20 m from the closest point of approach. Recorder 1 (denoted H1) was located 1 m above the lakebed and recorder 2 (H2) was 3 m above the lakebed. The background noise levels in Fig. 2 show excellent agreement between the recorders, with an average difference of 0.7 dB across all decidecade bands and a peak difference of 1.5 dB (20 Hz band). The increase in the noise levels at higher frequencies is most likely due to self-noise. The trials were conducted by performing 3 double runs at 4, 6, 10, and 20 kn for both vessels. Background noise levels were monitored throughout and showed very little variation. A schematic of the trial is shown in Fig. 3. An underwater camera (GoPro Hero 11) was fitted to the EB to enable the cavitation to be visualized and to determine the cavitation inception speed.

C. Data analysis

The source levels (L_s) have been computed from the received levels (L_p) using the smoothed semi-coherent image method (Yubero *et al.*, 2025). This method has been developed specifically for calculating vessel source levels in shallow water. A source depth of 0.3 m has been used for both vessels, which corresponds to the static depth of the propeller hub.

Decidecade band and narrowband results have been obtained by splitting the data window length into 1 s intervals with a 50% overlap. A Hanning window is then applied and a power spectral density estimate obtained with a frequency resolution of 1 Hz. The power spectral density estimates are then averaged over before converting to a logarithmic scale using a reference pressure of $p_{ref} = 1$ μPa. The decidecade band source levels presented in the following section are obtained by averaging over all runs and across both hydrophones. Decidecade bands are defined as per ISO 18405 (2017). Narrowband data are presented as received levels at H1 and are for a single run.

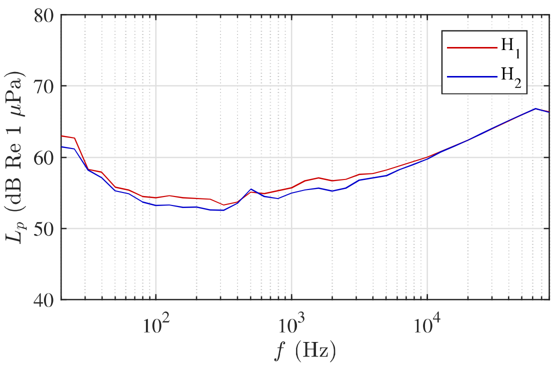


FIG. 2. Decidecade band background noise levels measured by the two recorders.

D. Uncertainty analysis

Uncertainty analysis has been conducted to determine the repeatability of the experiments. The standard deviation of the received levels for each vessel at all four speeds is presented in Fig. 4. This has been computed using all 6 runs. As expected, the standard deviation is higher at low frequencies but is generally below 3 dB. The higher uncertainty at 10 kn is likely due to the running attitude of the vessel at this speed. At 10 kn, both vessels were just planing, and at this speed small changes in engine speed, wind speed, and loading condition can have a significant impact on running attitude and hence the radiated noise levels. Overall, the uncertainty levels are comparable to those in other published works (Smith *et al.*, 2024b; Smith *et al.*, 2025).

A comparison of the results going in the different directions is presented in Fig. 5. This shows that there is minimal difference in the results going in the two directions past the recorders. This shows that wind effects were minimal.

III. RESULTS AND DISCUSSION

A. Source levels

The decidecade band 1 m equivalent source levels are shown in Fig. 6 for both vessels. The results are reported over a frequency range of 20 Hz $\leq f \leq$ 80 kHz. It should first be noted that, despite the low background noise levels and the relative closeness of the recorders, the low-frequency noise from the EB was very difficult to measure. At 4 kn, the noise levels below around 200 Hz were indistinguishable from the background noise levels. At speeds of 6 kn and above, reliable measurements (greater than 3 dB above background levels) were still not possible for frequencies below 80 Hz. For the ICEB, only frequencies below 30 Hz had to be disregarded at 4 kn and those below 25 Hz at 6 kn.

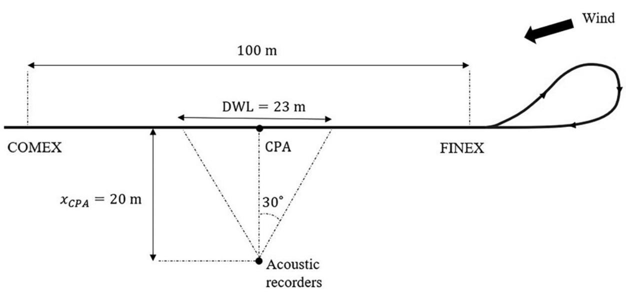


FIG. 3. Schematic of the trial setup.

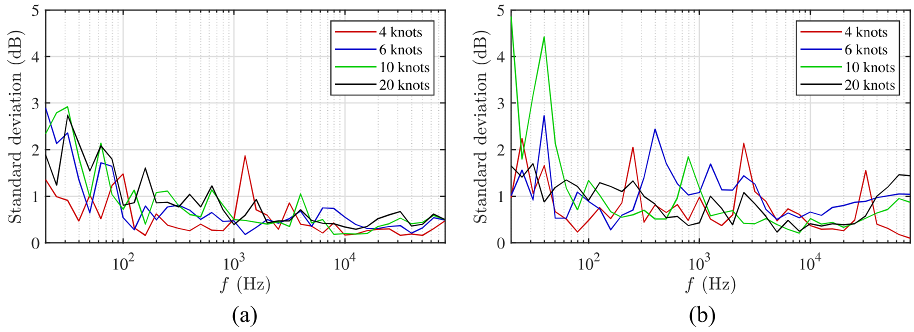


FIG. 4. Standard deviation of the received levels for (a) ICEB and (b) EB.

Where a given decidecade band is less than 3 dB above the background noise, it has not been directly included. Where the level is between 3 and 10 dB of the background noise, the background noise has been subtracted off. No corrections have been made where a given decidecade band is more than 10 dB above the background noise. In cases where the measured level is within 3 dB of the background noise, the background noise is taken as a ceiling, and the 1 m equivalent level is computed using this and shown with a dotted line in Fig. 6. In other words, the dotted line represents the maximum that the true source level could be.

Looking at the results in Fig. 6 and the broadband source levels in Table II, a number of things are immediately apparent. First, the EB is quieter than the ICEB across the speed range. As expected, the difference reduces at higher speeds due to cavitation becoming increasingly dominant. At 4 kn, the broadband source level is 122 dB re 1 μPa m for the EB and 165 dB re 1 μPa m for the ICEB, representing a 43 dB difference. This difference reduces to 10 dB at 20 kn. The source level for the EB increases monotonically with speed, but the same is not true for the ICEB. Indeed, this is louder at 4 kn than at any other speed and possible reasons for this are discussed in the following section. The broadband source level decreases to 157 dB re 1 μPa m at 6 kn before increasing to 160 dB re 1 μPa m at 10 kn. A slight decrease is then observed at 20 kn, with a source level of 159 dB re 1 μPa m. Notwithstanding the unusually high noise level at 4 kn, these results are comparable to data from rigid-inflatable boats of a similar size and power (see, e.g., Picciulin *et al.*, 2022; Smith *et al.*, 2024b; Smith *et al.*, 2025).

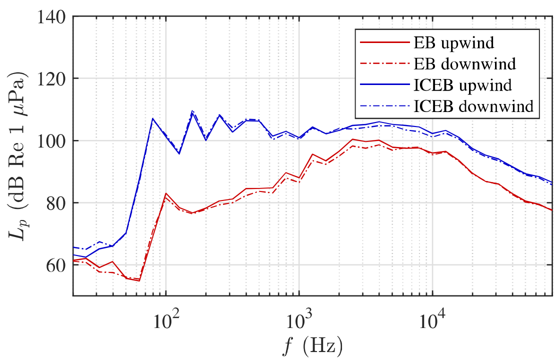


FIG. 5. Decidecade band received levels for the two vessels at 6 kn traveling upwind and downwind.

The broadband source level for the EB rises from 134 dB re 1 μPa m at 6 kn to 148 dB re 1 μPa m at 10 kn. It then rises only slightly to 149 dB re 1 μPa m at 20 kn. The relative insensitivity of the source level to speed over this range has also been observed in other works (see, e.g., Picciulin *et al.*, 2022), and has been attributed to changes in the running attitude of the vessel. In the present study, both vessels began to plane at around 10 kn. Once the vessel starts to plane, the propeller loading can reduce slightly and the reduced wetted area limits the transmission of machinery noise into the water. The noise sources, in particular the propeller, also become shallower once the vessel starts planning, which increases the free surface interaction effects.

B. Acoustical mechanisms

To understand the differences between the source levels of the two vessels and determine the driving factors, narrowband analysis of the results has been carried out. Figure 7 shows the received levels with a frequency resolution of 1 Hz for both vessels at each speed. The background noise levels are also shown to provide a point of reference and to show where the received levels are comparable to the ambient levels in the lake.

In the pre-cavitating regimen, the noise from a boat or ship is typically dominated by mechanical sources associated with the engine, which may be accompanied by tonal noise at the propeller blade rate and harmonics when there is sufficiently high spatial variability in the flow into the propeller. In the case of the ICEB, the engine firing rate and harmonics are clearly visible in the spectrum [see Fig. 7(a)], with the first harmonic dominating the acoustic spectrum. The engine tones are superimposed on a broadband hump, which is centered around approximately 150 Hz. Based on previous research into noise from internal combustion outboard engines (Smith *et al.*, 2025), this is due to the exhaust gases which are expelled through the propeller hub.

For the electric boat, the noise levels below 180 Hz are indistinguishable from the background noise levels [see Fig. 7(b)]. Above this, the noise is primarily broadband. The blade rate is not visible in the spectrum nor are any of the harmonics. At higher frequencies, distinct tonal noises can be seen. In particular, there is a prominent tone at 32 kHz with three equally spaced tones either side. This is due to

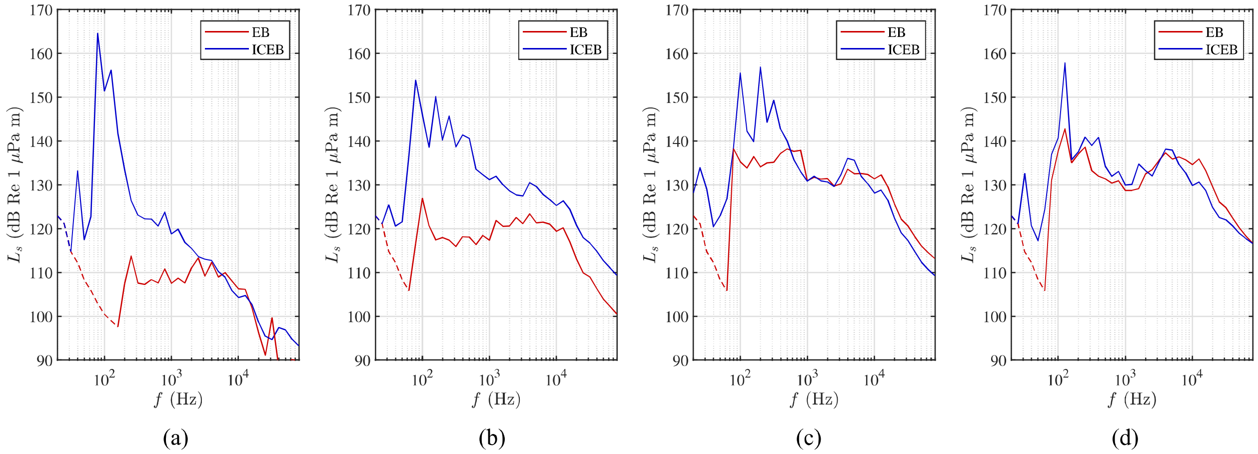


FIG. 6. Decidecade band source levels for the two boats at (a) 4 kn, (b) 6 kn, (c) 10 kn, and (d) 20 kn. Dotted line indicates where the received level was indistinguishable from the background noise.

the motor control discussed in Sec. I. It is interesting to note that the levels of this noise are substantially below those reported by Gaggero *et al.* (2024), where the motor was far less powerful than the one considered here. When converted to 1 m equivalent levels, the peak tone here is 83 dB re 1 μPa m, compared with tones exceeding 130 dB re 1 μPa m reported by Gaggero *et al.* (2024). Detailed specifications of the power electronics of the two propulsion systems are not available, but it is known that the motor in the propulsion system tested by Gaggero *et al.* (2024) is in the hub, whereas the motor in the present study is above the waterline and connected to the propeller using an L-drive. The differences in noise levels produced by the power electronics suggest that the propulsion architecture and power electronics design could have a significant impact on the generation of high-frequency noise.

At 4 kn, neither vessel propeller is properly cavitating, but there is evidence of bubble-induced cavitation as shown in Fig. 8(a). This is where pre-existing gas bubbles from the surface get close to the propeller where they can become entrained in the vortex core and expand rapidly. This has been observed on other small vessels at this speed (Smith *et al.*, 2025). However, because it is intermittent in nature and because the resulting cavity contains a significant percentage of non-condensible gas, its overall contribution to the noise level is low.

At 6 kn, the propellers on both vessels are cavitating. This has been confirmed using camera footage for the EB [see Fig. 8(b)] and by the sharp rise in high-frequency noise for both vessels, as can be seen in Figs. 7(c) and 7(d).

TABLE II. Broadband source levels ($L_{S_{BB}}$) computed over $20 \leq f \leq 80\,000$ Hz (dB re 1 μPa m).

Speed (kn)	ICEB	EB
4	165	122
6	157	134
10	160	148
20	159	149

Interestingly, the blade rate is still not visible in the narrowband spectrum for either vessel. However, a tone at the twice the blade rate is visible for the EB. Noise at the blade passing frequency is usually weaker in the pre-cavitating regimen, although it is usually measurable. Previous studies on small high-speed propellers have shown that tonal noise at this frequency can rise sharply once cavitation is present (see, e.g., Smith *et al.*, 2025). A possible explanation for the absence of this tone is the hullform design. Because the boats are catamarans with the engine mounted on the centreline, the flow into the propeller has less spatial variability than for a propeller mounted behind a monohull. This provides an explanation for the tone at twice the blade rate for the EB. The location of the propeller relative to the demihulls means that it will experience a degree of variability in the inflow twice with each revolution. The location of the propeller relative to the demihulls can also explain why the signature of the tip vortex cavitation is not as expected. In particular, the prominent broadband hump, which typically occurs with a center frequency of around 4–7 times the blade passing frequency, is missing. Pennings *et al.* (2016) showed that tip vortex cavitation produced relatively little noise when the upstream flow was uniform. The introduction of upstream spatial variability in the flow gives rise to the broadband hump and a sharp increase in noise at the blade passing frequency. This suggests that the low-frequency acoustic contribution from the cavitation is less because of the hull geometry, highlighting the importance of always considering the hullform design in the context of propeller cavitation.

Despite the onset of cavitation, the acoustic spectrum for the ICEB remains dominated by engine tones. These tones are responsible for most of the low-frequency noise seen in Fig. 6, meaning that engine noise remains dominant across the speed range for this vessel. This is unusual but has been observed before on a rigid-inflatable boat (Smith *et al.*, 2024b). In this case, the dominance of the engine is partly due to the reduced propeller noise for the reasons described above. It is also interesting to note that there is no

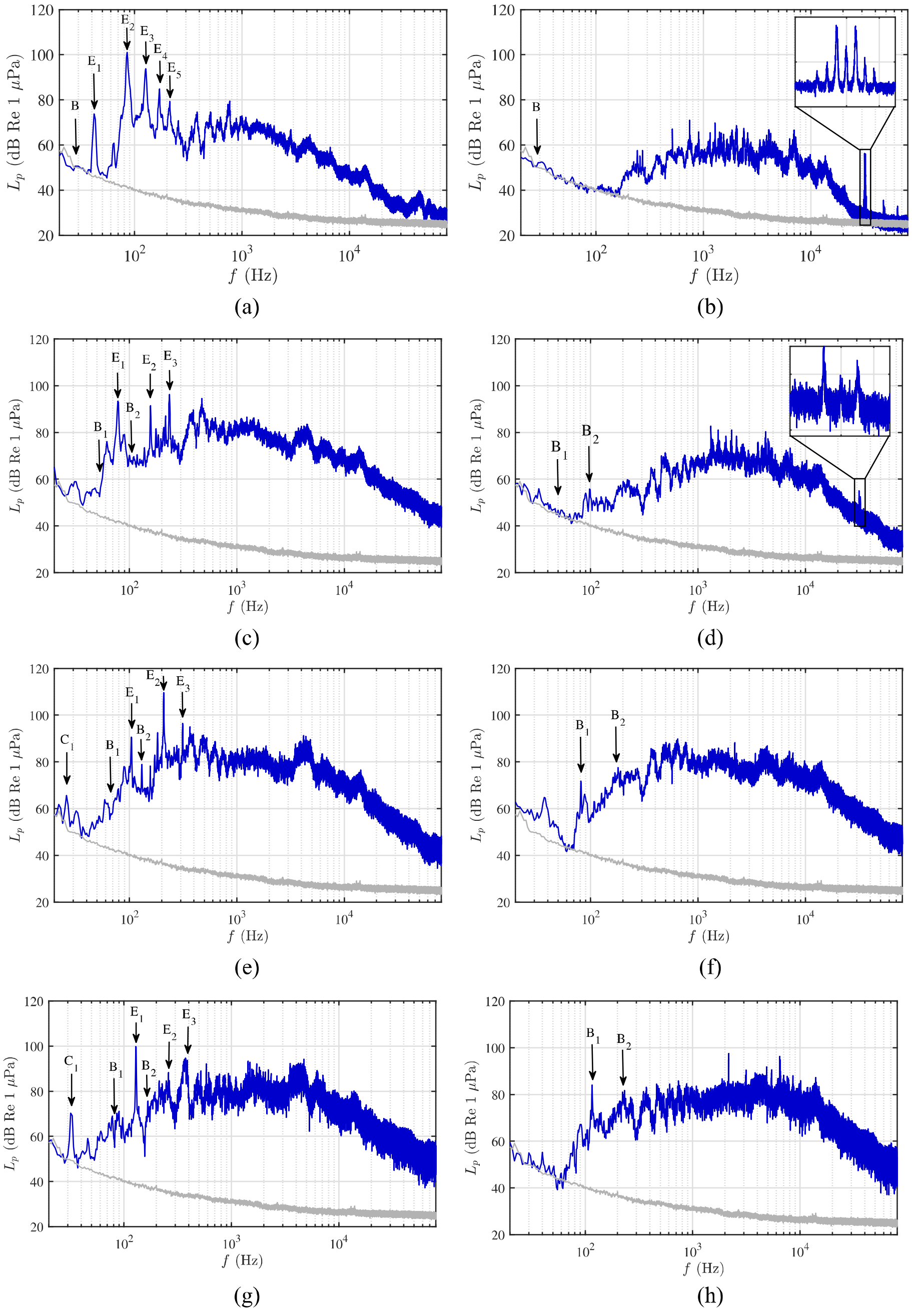
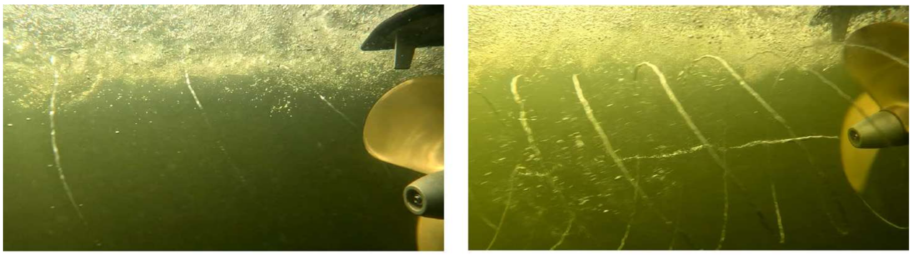


FIG. 7. Blue represents the narrowband received levels (at H1) for the EB and the ICEB. Left: The ICEB spectrum. Right: The EB spectrum. (a), (b) 4 kn; (c), (d) 6 kn; (e), (f) 10 kn; (g), (h) 20 kn. The background levels are shown in gray for comparison. A frequency resolution of 1 Hz is used. Cylinder and engine firing rates are denoted C and E, respectively; B indicates the blade rate.

correlation between the amplitude of these tones and speed. Previous studies of small boat noise (Smith *et al.*, 2024b) have suggested that much of the underwater noise originating from the outboard is transmitted into the water by the hull. Therefore, the resulting noise depends on the running attitude of the vessel and the structural dynamics of the hull and engine mounting as well as the source amplitude. This helps to explain the weaker relationship between speed and noise than might be expected.

The lack of engine noise from the EB means that the acoustic spectrum becomes dominated by cavitation noise very quickly once present. However, as with the ICEB, this is predominantly at higher frequencies and is assumed to be due to bubble collapse. At 6 kn, the high-frequency noise from the EB is less than for the ICEB. At this speed, the propeller rotation rate for the two vessels is very similar: 16.6 Hz for the EB and 17.2 Hz for the ICEB. However, the reduced pitch of the EB propeller will likely result in a weaker vortex strength with a higher core pressure. This, in turn, reduces the collapse strength. Despite the increased pitch of the ICEB propeller, the rotation rate is similar to that of the EB propeller at this vessel speed. While this may be partly attributable to differences in section design and blade-area-ratio, the hub-diameter ratio is also relevant here. In common with most conventional outboard propellers, the ICEB propeller has a high hub-diameter ratio to accommodate the through-hub exhaust. All else equal, a propeller with a larger hub-diameter ratio has less useful lifting



(a) (b)

FIG. 8. (a) Bubble-induced cavitation at 4 kn and (b) developed tip vortex cavitation and intermittent hub vortex cavitation at 6 kn. Photographs taken by the authors.

surface and so must turn more quickly to produce the same thrust compared to one with a lower hub-diameter ratio. This suggests that it may be possible to have a lower-noise propeller for an electric outboard than a conventional outboard. Further research would be useful here to confirm and quantify this.

At higher speeds, the reduced propeller pitch on the EB becomes detrimental, with the propeller turning at a much higher speed than the one on the ICEB. At 20 kn, the propeller is turning at 39 Hz on the EB but only 28 Hz on the ICEB. The associated cavitation numbers (based on tip speed) are 0.12 for the EB and 0.24 for the ICEB. The positive correlation between the shaft speed (and hence cavitation number) and the levels of high-frequency noise means that it is reasonable to assume that this noise is predominantly due to cavitation, particularly the collapse phase.

At 10 and 20 kn, a tone at the blade passing frequency is visible for the EB in addition to the tone at twice the blade rate, but the mechanism responsible for its appearance (as compared with lower speeds) is not clear. Apart from this, the spectrum is mostly broadband: made up of a combination of flow noise, spray, and cavitation. The high-frequency noise from the power electronics is still visible at 6 kn [see Fig. 7(d)] but not at 10 or 20 kn. Apart from the change in the blade passing frequency, there is remarkably little change in the spectrum when going from 10 to 20 kn. The high-frequency broadband noise associated with cavitation collapse shows no significant difference, suggesting that the levels of cavitation are broadly the same at the two speeds. Tones at the blade rate and twice the blade rate do emerge for the ICEB at higher speeds, but their amplitude remains low compared to the engine noise. The frequency content of the high-frequency noise remains fairly constant for the ICEB at 10 and 20 kn. The levels do increase modestly, most notably at the highest frequencies, but far less than would be predicted in the often-used power law scaling for high-frequency cavitation noise (Ross, 2013). Possible reasons for the less-than-expected increase in cavitation noise have been discussed in Smith *et al.* (2024b) and Smith *et al.* (2025) and have been linked to the nature of tip vortex cavitation and changes in propeller loading due to changes in running attitude.

IV. CONCLUSION

This study has compared the URN levels for two similar boats: one powered by a conventional internal combustion outboard engine and one with an electric outboard. The aim was to provide comparative data for the source levels across a wide speed range, and to identify the noise sources and how they change with speed.

The results show that the noise levels for the electric boat are substantially lower than those for the internal combustion engine boat. The differences are greatest at low speed, where low-frequency noise associated with the engine dominates for the internal combustion engine boat. The cavitation inception speed is around 6 kn for both vessels, although cavitation appears to develop slightly later on the electric boat due to the different propeller on this vessel. High-frequency tonal noise due to the motor control is measurable on the electric boat but lower than in other published studies, highlighting the importance of the design and architecture of the motor and power electronics.

From an animal perspective, these results indicate that the use of electric propulsion on small vessels does offer some advantages for reducing URN impacts. In particular, the use of electric propulsion eliminates the low-frequency noise associated with combustion processes and the expulsion of exhaust gases through the propeller hub (Smith *et al.*, 2025), substantially lowering noise at these frequencies and thereby reducing exposure and potential disturbance to low-frequency hearing specialists. However, for species which have better high-frequency hearing capabilities (e.g., odontocete cetaceans and pinnipeds), the higher frequency broadband noise, particularly once cavitation is present and when speed increases, remains the dominant contributor to exposure regardless of propulsion type.

Consequently, to have the most benefit to the broadest range of marine fauna, effective management strategies should combine electric propulsion with measures which also seek to address cavitation noise. These include reducing vessel speeds (Findlay *et al.*, 2023), modifying propulsion architecture, optimizing the flow into the propeller as well as the propeller design, (Smith and Rigby, 2022). Care must also be taken to ensure the motor and power electronics do not result in significant levels of high-frequency tonal noise. Together, this combined approach can offer pathways to reduce the impacts of small vessel noise on marine fauna, and further support the design of electric propulsion systems which continue to reduce underwater noise pollution.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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