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Underwater radiated noise from small craft in shallow water: Effects of speed and running attitude[☆]

Tom A. Smith[a,*], Andrea Grech La Rosa[a], Bill Wood[b]

[a] Department of Mechanical Engineering, University College London, Torrington Place, London, WC1E 6BT, United Kingdom
[b] BMT, Legget Drive, Ottawa, K2K 1Z8, Canada

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ABSTRACT

Underwater radiated noise from marine vessels is a growing problem, with a large body of evidence now showing the detrimental impact this is having on marine life. Whilst most of the discussion currently focusses on the impact of large vessels, recent evidence shows that small vessels can dominate the soundscape in shallow coastal waters. In this study, acoustic trials are carried out on two small vessels: a pilot boat and a rigid inflatable boat (RIB) across a wide speed range. The average source levels range from 156–173 dB for the pilot boat and 164–166 dB for the RIB (re 1 μPa m). The engine noise is dominant for the RIB across the speed range, and it is further shown that the heading relative to the prevailing waves is a bigger determining factor for noise levels than speed. In upper sea state 3, the overall sound level is up to 6 dB higher when in head waves compared to following waves. Acoustic measurements are combined with onboard vibration measurements to provide further insights into the relationship between noise and vibration. Analysis of this data shows the vessel running attitude plays a key role in determining how much noise is transmitted into the water.

1. Introduction

Underwater noise resulting from human activity is a growing problem with increasing numbers and sizes of vessels contributing to a significant rise in the ambient noise levels in seas, oceans, and waterways around the world (Erbe et al., 2019; Chou et al., 2021). These noise levels are having a detrimental impact on many marine ecosystems, leading to growing calls for better regulation and legislation of marine activities with regards to the noise produced. For naval operations, the importance of underwater noise as a means of detecting vessels has long been understood. This has led to continuous development in sonar and hydrophone technology, matched by a continual need to reduce the radiated noise from both surface vessels and submarines.

Over the past couple of decades, a large body of evidence has built up showing the negative impacts of anthropogenic noise from shipping and other marine traffic on marine life. This includes cetaceans (Nowacek et al., 2007; Dyndo et al., 2015; Wisniewska et al., 2018), and many species of fish and invertebrates (Simpson et al., 2016; Mickle and Higgs, 2018; Murchy et al., 2019). Alongside this, numerous studies have been conducted to determine the radiated noise levels from commercial and other vessels: both to investigate the noise produced by specific vessels (Arveson and Vendittis, 2000; McKenna et al., 2012; Li et al., 2018; Picciulin et al., 2022) and also to measure and monitor noise levels from shipping in a particular area (Farcas et al., 2020; Lalander et al., 2021; Putland et al., 2022). Despite much of the focus in recent years being on the impact of large commercial vessels, recent evidence has suggested that small vessels could be contributing more to the overall soundscape than previously acknowledged, particularly in shallow coastal waters (Parsons et al., 2021; Hermannsen et al., 2019; Cope et al., 2021). These studies have highlighted the need to better understand the levels of noise from small vessels and the impact this is having on marine life in the areas where they operate. This issue is becoming particularly important for marine protected areas (MPAs). Many countries have signed up to protect 30% of their coastal waters by 2030, and it is recognised that this must consider noise pollution. However, acoustic monitoring of some MPAs has shown that small vessels are leading to significant and potentially harmful increases in noise levels (Wilson et al., 2022).

Shallow coastal waters present a particular challenge for operational, geographical, naval and ecological reasons. Firstly, many such areas have a high concentration of marine traffic due to vessels entering and leaving ports and harbours, ferries, and recreational vessels which

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* Corresponding author.
E-mail address: tom.smith.17@ucl.ac.uk (T.A. Smith).

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mostly operate close to shore. Secondly, shallow coastal waters are home to a large percentage of marine biodiversity, including marine mammals, birds, fish, and invertebrates. Sound propagation in shallow water is complex and depends on the frequency, range, water depth, bottom topography and substrate material. This can lead to propagation losses that are lower or higher than in deep water, depending on the frequency, depth, seabed material and distance under consideration, Ainslie et al. (2014). Low frequency noise can attenuate more rapidly in shallow water (MacGillivray et al., 2023), with the effects becoming more pronounced as the wavelength-to-water depth ratio increases, although this depends partly on the reflection at the seabed, which is a function of the substrate material.

Human impact on ecosystems and wildlife is coming into much sharper focus outside of academic communities, and this is increasing the pressure on governments and other bodies to reduce the impact our actions have on the natural world. During the lockdowns imposed during the COVID pandemic, there were many reports in local and national media of animals being sighted in places they would not normally be found, or in larger numbers. There were multiple reports of seals much further up the River Thames[1] and also in parts of the Solent[2] where they are rarely seen. Seals are known to be very sensitive to human activity with several studies showing that seals avoid noisy marine environments (Halliday et al., 2020). As well as highlighting the impact we are having on these habitats, this also shows us that wildlife can adapt and recover if given the chance.

Regulations and legislation on underwater noise from human activities is limited at present, particularly for smaller vessels. Many classification societies have "quiet ship" notations, but such notations are primarily for larger commercial or research vessels and cannot be readily applied to small recreational boats. There are currently no international regulations limiting the noise produced by smaller vessels, and underwater radiated noise is rarely prioritised by designers and builders. Much of this stems from a lack of data showing what the noise levels are and what impact this has, as well as a lack of economic incentives to make improvements. Despite increased interest in measuring noise levels from specific vessels and specific areas of water, the lack of data remains a major obstacle, both in terms of bringing in new legislation and also to designers and boat and ship builders who need to reduce the noise their vessels produce. Recent works that will help improve this are (Ainslie et al., 2022; MacGillivray et al., 2023), where it is shown that reliable and repeatable sound levels can be obtained for vessels in shallow water. This is crucial for small vessels, which mostly operate close to the coast and generally in shallow water. These works provide guidance on experimental setup and calculation of propagation losses, taking into account seabed and sea surface effects. Having such methods is crucial for comparing the acoustic data for different vessels and developing standards against which vessels can be designed and certified.

A wide range of noise reducing technologies have been developed over past decades, often for naval vessels or cruise ships, and many more are at earlier stages of development (Smith and Rigby, 2022). However, such technology is seldom considered for smaller vessels and much of it has struggled to get beyond the prototype stage. Some vessels such as fisheries research vessels do give consideration to radiated noise, but these make up only a very small percentage of small vessels around the globe. Technologies such as passive isolation mounts can be very effective at reducing engine and machinery noise, but are rarely used on small vessels due to cost and space constraints. Similarly low noise propulsion technologies, often developed in the naval sector, have struggled to find their way onto smaller commercial vessels. There are three reasons for this: cost, incentives, and enough data to demonstrate the effectiveness of the technology outside of laboratory tests. These issues need to be considered together: without demonstrating the effectiveness of noise reducing technologies in a real-world environment, vessel builders and operators will be reluctant to invest in them. From a regulatory perspective, it is challenging to bring in mandatory noise limits as there is insufficient data on how much noise most vessels produce. Furthermore, there is insufficient evidence as to how much the noise levels might be reduced should particular technologies be adopted. It is clear then that significant investment in research and development is needed to obtain more data on noise levels from existing vessels, and to develop at-scale prototypes of noise reducing technologies.

From an operational perspective, speed is generally considered the dominant factor for radiated noise levels. Some coastal waterways such as river estuaries and harbours have speed restrictions in place for safety reasons and to reduce erosion, and there is strong evidence that reducing speed can be effective at reducing noise levels for many large commercial vessels (MacGillivray et al., 2019; Findlay et al., 2023) particularly if the reduced speed eliminates cavitation. Many trials have shown that a positive relationship exists between speed and radiated noise levels for large ships (for example Arveson and Vendittis, 2000), but the relationship is seldom linear due to changes in propeller loading, the emergence of cavitation, propeller singing, and other phenomena. However, a number of studies have shown that some vessels can produce more noise at lower speeds than higher speeds. This can occur for a variety of reasons. For example in one study (Svedendahl et al., 2021), it was found that one of the boats tested produced more noise at 9 knots than at 18 knots. Underwater cameras revealed that this was due to the cavitation being worse at 9 knots, and it was noted that the propeller was designed for speeds above 20 knots. For vessels fitted with controllable-pitch propellers (CPP), reducing speed through a pitch-reduction rather than a shaft speed reduction can also lead to increased noise levels (Tani et al., 2015). Reducing propeller pitch at constant shaft speed can lead to significant levels of pressure-side cavitation as well as other types of cavitation due to the propeller operating in an off-design condition. Thus, the effectiveness of speed restrictions will depend on the type of vessel and its propulsion architecture, and further research is needed to provide a more complete understanding of how speed and noise relate on a broader range of vessels.

Despite a number of recent studies providing data on the noise from small craft and the impact they are having on the environment (as described previously), there remain gaps in our understanding of this issue and more data is needed across more vessel types and operating conditions. In particular, comprehensive datasets covering the entire speed range of a vessel are lacking, making it difficult to understand how sound levels change as a function of speed and why. It has been suggested that the running attitude of a vessel, for example whether or not it is planing, is important (Erbe et al., 2016) and this likely contributes to the nonlinear relationship between speed and radiated noise levels (Parsons and Meekan, 2020). Furthermore, in order to obtain reliable 1 m equivalent source levels for a given vessel, trials are typically carried out in very benign weather conditions. This does not allow the effects of weather and vessel heading relative to the prevailing weather to be assessed. Small vessels are far more affected by low to moderate sea states than large vessels owing to their lower displacements and lengths relative to prevailing wavelengths. Added resistance due to waves increases propeller and hence engine loading (Molland et al., 2017) and so this is likely to have a measurable effect on the radiated noise levels.

In this work, the results of acoustic trials on two small vessels: a pilot boat (PB) and a rigid inflatable boat (RIB) are presented. The mean water depth in the trial area was 27 m, which is considerably shallower than the 150 m depth required by standards such as ISO17208-1 (2016). However, small vessels operate in shallower waters and so it is of interest to experimentally measure the relationship between received levels and source levels in such conditions. Recent

[1] www.thamesestuarypartnership.org.

[2] www.advertiserandtimes.co.uk.

studies into small boat noise have generally been carried out in shallower water than required by this standard, with depths as low as 10 m being reported (Parsons and Meekan, 2020). The issue of water depth for acoustic trials is currently being discussed by the underwater acoustics community and shallow water standards are being developed (see Ainslie et al., 2022; MacGillivray et al., 2023 for details on this). To ensure reliable and repeatable data can be obtained for this study, four hydrophones have been placed at two distances from the vessel to enable the transmission losses to be used to estimate the propagation loss from the source to the hydrophones. This has been combined with propagation loss models that consider the effects of water depth, source depth and seabed material to provide a better understanding of how the noise propagates away from the source.

The trials have been conducted across a broad speed range to provide insights into how the radiated noise levels and frequency content vary as a function of speed. The measurements have been supplemented by data from accelerometers mounted onboard the vessels to provide an understanding of how the vibration levels onboard vary with speed and how this correlates with changes in underwater radiated noise. The purpose of this study is to provide a more complete understanding of small boat noise in the environment they typically operate in: namely shallow water that is not necessarily calm. The data also provide insights into the effect of water depth on the source levels and how a frequency-dependent propagation loss can change how we interpret the source levels for these vessels. Furthermore, trials were conducted to assess the impact of vessel heading relative to the prevailing weather, something that has not previously been reported on.

2. Methods

2.1. Trial location and vessel descriptions

The trials were conducted over a two day period from 7th–8th July, 2023 off the south coast of the UK, in Bigbury Bay. The water depth during the trial was measured using an echo-sounder and had an average depth of 27 m. The bathymetry in the trial area is fairly smooth, with the depth gradually increasing away from the coast. Samples taken from the seabed showed that the upper layer is a mixture of sand and mud. During the trials, local marine traffic was monitored using an AIS receiver and also visually, and no other vessels were identified within 5 km of the trial location or visible during the trials. The weather conditions, based on forecast data and observations, were Beaufort 4 with a mean wind speed of 12 knots, and the sea state was upper 3/lower sea state 4, with an estimated significant wave height of 1–1.5 m. The water temperature in the area of the trial was 16 degrees Celsius, leading to a speed of sound of $c_w = 1504$ m/s (Mackenzie, 1981).

The two vessels used were a pilot boat (PB) and a rigid inflatable boat (RIB). The pilot boat is a Lochin 33 with a composite hull and the RIB also has a composite hull. The particulars of each vessel are given in Table 1. These vessels were chosen because their designs are very common. RIBs are widely used around the world and have a relatively common design with hard-chine hullforms and outboard engines. The RIB used here has a single 4-stroke petrol outboard engine with a 3-bladed propeller. The maximum speed is 26 knots in the conditions encountered during the trial. The pilot boat size, design and propulsion architecture is quite typical of many small fishing vessels, support vessels and leisure vessels. It is powered by twin inboard diesel engines and twin shafts with 4-bladed propellers. The engines are 4-stroke and have 4 cylinders. The maximum speed of the pilot boat is 16 knots for the trial conditions.

Table 1
Principal particulars of the vessels used for the trial.

	Pilot boat	RIB
Length overall (m)	9.9	7.2
Beam (m)	3.5	2.6
Static draught (m)	0.6	0.35
Max engine power (kw)	2×177	129
Max shaft speed (rpm)	3300	5500–6100
Number of propellers	2	1
Number of blades (z)	4	3
Gearbox ratio (g)	2.0	2.5

2.2. Experimental methods

As discussed in the introduction, there is not currently an internationally agreed standard on measuring underwater noise from small vessels in shallow water although one is in development at the time of writing. However, existing standards can be tailored and used in conjunction with other published works to ensure the trial is carried out in a reliable and repeatable manner. In this work, the terminology in ISO18405 (2017) is adopted, and much of the methodology follows that set out in ISO17208-1 (2016) and ISO17208-2 (2019). Departures from this relate to the water depth and the calculation of the propagation losses, and these are discussed further in this section and in Section 2.3.

For each run, the vessel being assessed travelled 500 m in a straight line from the COMEX to FINEX points (see Fig. 1). The vessel's speed was kept as constant as possible during this time and was at the desired speed before commencing each run. The data window length (DWL) used for the subsequent analysis of the noise levels was 100 m and the sensitivity of the results to this distance is discussed in Section 2.4. The underwater noise measurements were made using four RS Aqua/Turbulent Research Porpoise acoustic recorders. These are single-channel acoustic recorders capable of sampling at up to 384 kHz and with a dynamic range of 110 dB. These were arranged in two vertical arrays, denoted $R_{1_{a,b}}$ and $R_{2_{a,b}}$, at 40 m and 85 m from the closest point of approach (CPA), as shown in Fig. 1. The hydrophones were located closer to the CPA than is required for deep water trials (ISO17208-1, 2016), which requires a minimum distance of 100 m. However, recent work by Ainslie et al. (2022) suggests that locating the hydrophones within 4 water depths of the CPA is appropriate for shallow water trials provided that they are located within the far-field, as defined by ISO18405 (2017). This approach is adopted in this study. Arranging the hydrophones in this manner was done to capture the transmission losses, which can be significant at low frequencies when the source terms are close to the free surface as is the case for small vessels. This is discussed further in Section 2.3. The acoustic recorders are negatively buoyant and so were held in place by floats, as shown in Fig. 2. Two hydrophones were placed at each distance to account for spatial variability in the acoustic field and reduce the uncertainty in the results. Each of the hydrophones was calibrated by the manufacturer prior to the trials and has its own sensitivity, and typical sensitivity values are −160 dB re 1 V/μPa. The sample frequency is $f_s = 192$ kHz. Background noise measurements were made throughout the trials and used to ensure the validity of any given run. This process is described in more detail in Section 2.3.

Multiple speeds were assessed for each vessel (see Table 2) and at least two double runs were carried out at each speed. GPS onboard both vessels was used to monitor speed and location throughout. On the first day of trials, the weather was on the beam of the test vessel whereas on the second day it was bow/stern quartering. All trials of the pilot boat were conducted on day 1 and trials of the RIB were conducted on day 2.

In addition to the acoustic measurements, vibration measurements have also been obtained for both vessels. Piezoelectric accelerometers with a frequency range of 10–8000 Hz were mounted at different

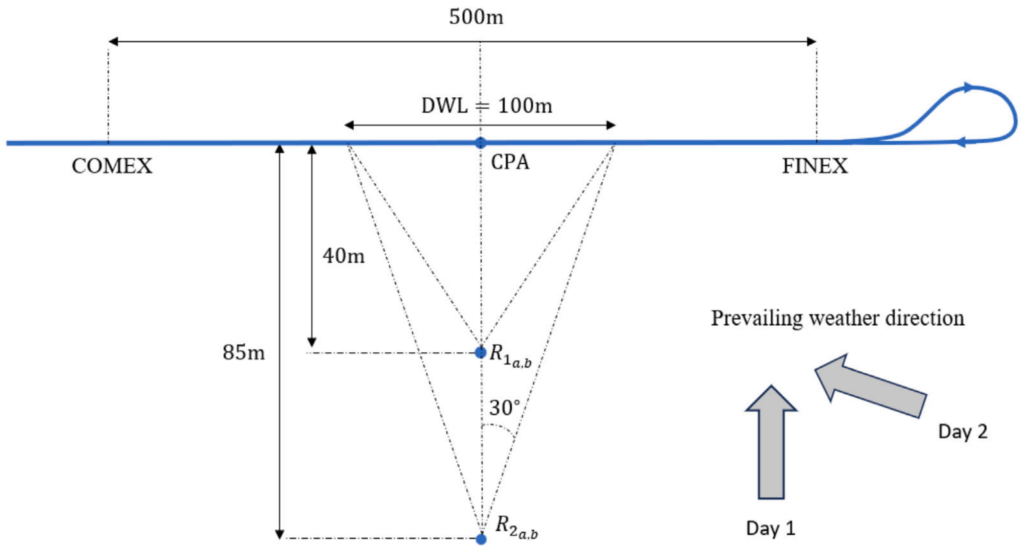


Fig. 1. Schematic showing how the trials were conducted. Data window length (DWL) and distances to hydrophone arrays are shown. Not to scale.

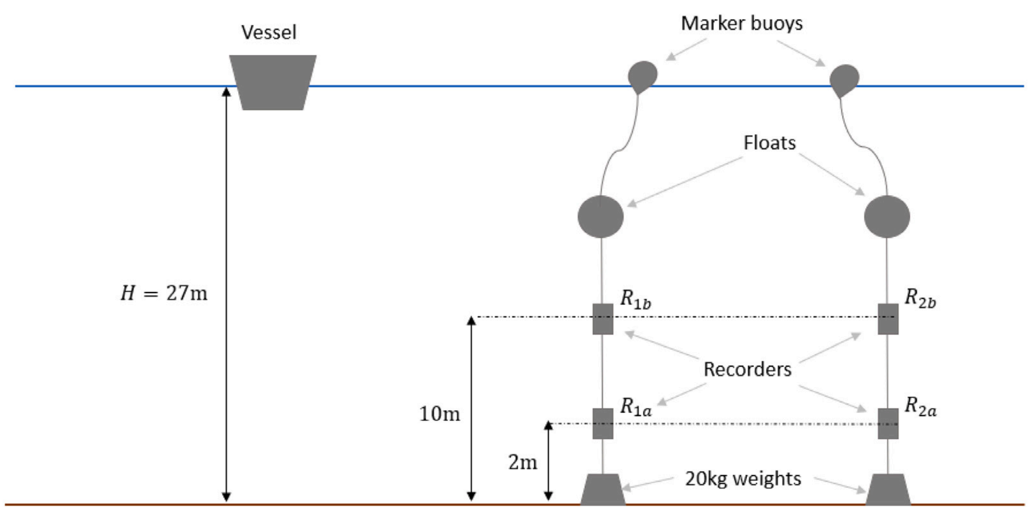


Fig. 2. Schematic of the hydrophone configuration. Not to scale.

Table 2
Speeds assessed for each vessel.

Vessel	Speeds assessed (knots)	Engine speed (RPM)
Pilot boat	6,10,14,16	1350–2700
RIB	6,10,14,18,22,26	2200–5000

locations and recordings taken for each trial. For the RIB, vibration sensors were located on the inside of the hull at midships. For the pilot boat, one accelerometer was mounted on the inside of the hull close to the bow and another was mounted on the deck at the transom. Sensors are mounted on the inside of the hull to capture the hull vibration that is transmitted into the water. This allows for the relationship between the hull as an acoustic source and the far-field noise to be investigated. Because of the different mounting points and structural design of the vessels, these measurements are not comparable from one vessel to the next and are not intended as absolute measurements of vibration. Instead, they are used to provide insights into how the vibration levels change with speed and weather conditions, and how this relates to the underwater noise.

The shaft speed was recorded for both vessels for each trial, enabling the cylinder firing rate (C), engine firing rate (E), and blade passing frequency (B) to be determined. Given that both engines are 4-stroke and have 4 cylinders, for a given shaft speed of N rpm, the cylinder and engine firing rates and their harmonics are given by

$$C = \frac{Ni}{120}\ , \qquad i = 1, 2, \ldots \tag{1}$$

$$E = 4Ci\ , \qquad i = 1, 2, \ldots . \tag{2}$$

The blade passing frequency and harmonics are

$$B = \frac{Nzi}{60g}\ , \qquad i = 1, 2, \ldots \tag{3}$$

where g is the gearbox ratio and z is the number of propeller blades.

2.3. Source level calculation

The source levels are obtained from the received levels recorded by each hydrophone by way of the propagation loss. There are two challenges with calculating the propagation losses for small vessels in shallow water. Firstly, as discussed in the introduction, acoustic propagation is more complex in shallow water due to seabed effects. Depending on the seabed material, more or less reflection will occur leading to different propagation losses and a complex spatial acoustic field.

Low frequencies may attenuate very rapidly, again depending on the water depth and seabed material (MacGillivray et al., 2023), although a seabed with a minimal impedance change compared with water will reduce this effect. Secondly, small vessels have lower draughts and so the acoustic source terms are much closer to the surface, amplifying the Lloyd's Mirror effect. A number of approaches have been developed for computing the propagation losses depending on the relevant factors, and two of these are described below. There are two purposes to this: to provide insights into how different factors influence the propagation losses and to compare the experimentally derived propagation loss with different analytical approaches. Further descriptions and comparisons of some of these approaches can be found in Meyer and Audoly (2022) and MacGillivray et al. (2023).

Firstly, using the notation set out in ISO 17208-2, we define the radiated noise level, L_{RN}, as

$$L_{\mathrm{RN}} = 20\log_{10}\left(\frac{p_{\mathrm{rms}}}{p_{\mathrm{ref}}}\right) + 20\log_{10}\left(\frac{r}{r_0}\right), \tag{4}$$

where p_{rms} is the root-mean-square of the acoustic pressure, $p_{\mathrm{ref}} = 1$ μPa is the reference pressure, r is the slant distance from source to receiver, and $r_0 = 1$ m. The source level, L_S, can then be obtained using the approaches discussed below.

2.3.1. ECHO certification alignment method (ECA)

This approach was developed as part of the ECHO certification alignment (Ainslie et al., 2022), and will be denoted "ECA" here. Like the ISO approach, this accounts for sea surface effects but not the seabed. The source level is defined as

$$L_S = L_{\mathrm{RN}} - \Delta L_{\mathrm{ECA}} + \Delta L_\alpha \tag{5}$$

where

$$\Delta L_{\mathrm{ECA}} = 10\log_{10}(\gamma). \tag{6}$$

ΔL_α is the loss due to energy absorption by seawater. Due to the relatively short distances considered in this study, this effect can be neglected (Ainslie and McColm, 1998). γ denotes the dipole to monopole conversion and is computed as follows:

$$\gamma(\theta) = 2 - \frac{\sin(2\pi T f_U) - \sin(2\pi T f_L)}{\pi T(f_U - f_L)} \tag{7}$$

where f_L and f_U are the lower and upper frequencies of each decidecade band and

$$T = \frac{2d_s\sin(\theta)}{c_w}, \tag{8}$$

where θ is the slant angle and d_s denotes the source depth. In ISO 17208, it is recommended that the depth of the source term be taken as 70% of the draught, which is 0.42 m for the pilot boat and 0.24 m for the RIB.

2.3.2. Seabed critical angle method (SCA)

The SCA method, described by MacGillivray et al. (2023), includes both sea surface and seabed effects. For the latter, the critical angle ψ must be obtained using

$$\psi = \operatorname{acos}\left(\frac{c_w}{c_s}\right) \tag{9}$$

where c_s denotes the speed of sound in the seabed with the assumption that the seabed is homogeneous. This is the angle at which all sound is reflected from the seabed and reduces as the seabed impedance approaches that of seawater. As discussed in Section 2.1, the seabed material at the trial location is a mixture of sand and mud, which has an estimated speed of sound of $c_s = 1700$ m s^{-1} (Chotiros, 1995).

The source level using this approach is

$$L_S = L_{\mathrm{RN}} - \Delta L_{\mathrm{SCA}} + \Delta L_\alpha \tag{10}$$

where

$$\Delta L_{\mathrm{SCA}} = 10\log_{10}\left(\sigma_1 + \frac{\psi r}{H}\sigma_\psi\right). \tag{11}$$

In Eq. (11),

$$\sigma_1 = \left(\frac{1}{2} + \frac{1}{4\eta\sin^2(\theta)}\right)^{-1} \tag{12}$$

$$\sigma_\psi = \left(\frac{1}{2} + \frac{3}{4\eta\sin^2(\psi)}\right)^{-1} \tag{13}$$

where

$$\eta = k^2 d_s^2. \tag{14}$$

2.3.3. Determination of propagation losses

To determine the validity of these approaches for the trial conditions, data from the two hydrophone arrays have been used to compute the transmission loss between array 1 (40 m) and array 2 (85 m) for different trial runs. Firstly, to determine the validity of a given run, the results are compared to background noise measurements. The approach for correcting or discarding a particular dataset followed the approach set out in ISO 17208-1. For a given decidecade band, if the background noise, L_{pn}, is at least 10 dB lower than that from a trial run, L_{ps+n}, no correction is made. If the background noise is within 3 dB of the trial run, the run is discarded. If $3 \le L_{ps+n} - L_{pn} \le 8$, then the background noise is subtracted from the trial data. Once any corrections are made to the trial data, the difference between hydrophones at the two distances has been calculated for each speed and averaged. This difference has then been used to obtain the frequency dependent coefficient, $A(f)$, in the formula:

$$\mathrm{TL}_{\mathrm{exp}} = A(f)\log_{10}\left(\frac{r}{r_0}\right) \tag{15}$$

which enables the overall propagation loss from the source to be estimated. Fig. 3 shows the experimentally derived propagation losses from the source to hydrophone R_{1a} for the RIB travelling at 22 and 26 knots. The curves are shown alongside the ECA and SCA methods with a source depth of 0.24 m. This figure tells us two things. Firstly, there is generally good agreement between the experimental results and the two analytical approaches, with a higher propagation loss at lower frequencies, tending towards a steady value for higher frequencies. Secondly, it is clear that the sea surface effect predominates the increased propagation loss at lower frequencies rather than the seabed. There is a slight reduction in the propagation loss due to seabed reflection, with the effect becoming larger at higher frequencies. This is due to a combination of the relatively small impedance between the seawater and seabed and the relatively short distance between the source and the receiver. This provides confidence that the analytical approaches can still be valid in shallow water, provided that the seabed is "soft" and the distances considered are relatively short.

To ensure a consistent approach, the source levels presented in the subsequent section have been obtained by computing the propagation losses for each hydrophone using the SCA method and then averaged. This allows for data from all four hydrophones to be utilised, reducing the experimental uncertainty of the derived results.

2.4. Uncertainty analysis

There are several sources of uncertainty when conducting trials to measure underwater radiated noise. ISO 17208 provides an overview of the sources of uncertainty for conducing deep water trials of large vessels, and these are mostly valid in this work. The exact location and speed of the vessel, propagation modelling, weather, and the sensitivity of the measuring equipment all contribute to the overall level of uncertainty. Many of these sources are minimised by experimental design, for

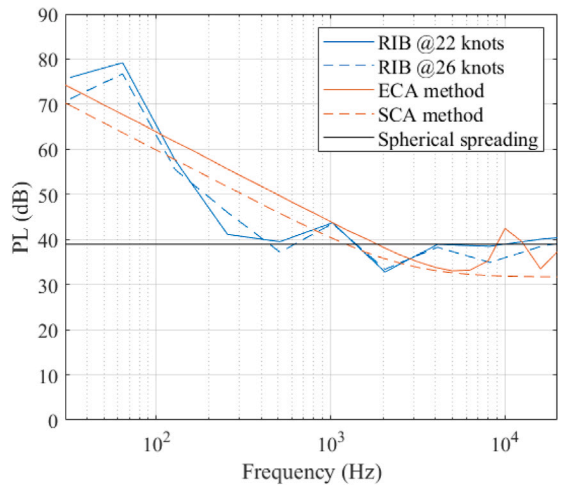


Fig. 3. Experimental and analytical propagation losses for CPA = 85 m.

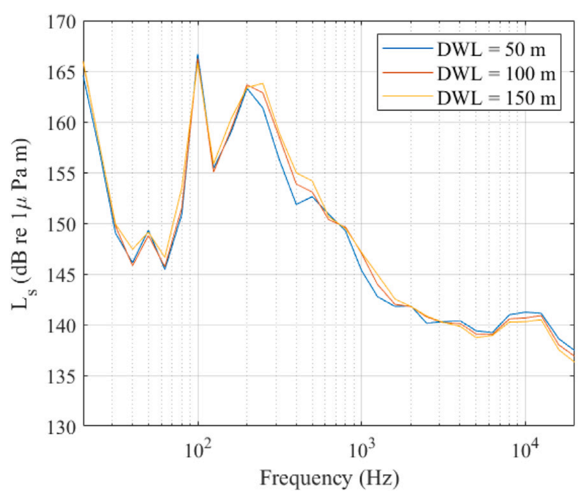


Fig. 4. Comparison of the decidecade band source levels for different data window lengths for the pilot boat at 16 knots.

example by using multiple hydrophones and by carrying out multiple runs in each condition.

However, there are additional sources of uncertainty when conducting trials of small vessels that merit further investigation. Firstly, the data window length (DWL) may have a significant effect on the results. In this work, the recommendation in ISO 17208 has been adapted, leading to a data window length of 100 m (as shown in Fig. 1). However, it is worth considering the effect of reducing or increasing this window length to provide a measure of the uncertainty this introduces. Phenomena such as slamming may only occur a few times per minute and with varying degrees of severity, and so too short a data window may lead to such an event being included in some runs but not others.

The effect of varying the data window length for the pilot boat at 16 knots is shown in Fig. 4 for lengths of 50, 100 and 150 m. This shows excellent agreement for DWL = 100 m and DWL = 150 m, and still reasonable agreement for DWL = 50 m. Overall this suggests the results are relatively insensitive to this measure. However, there is a small reduction in the standard deviation across the runs when going from DWL = 50 m to DWL = 100 m. For example, at f = 62.5 Hz the standard deviation for the trials at 16 knots reduces from 3.3 dB to 2.5 dB and at f = 125 Hz it reduces from 1.6 dB to 1.2 dB. There is minimal difference between the results for DWL = 100 m and DWL = 150 m. At higher

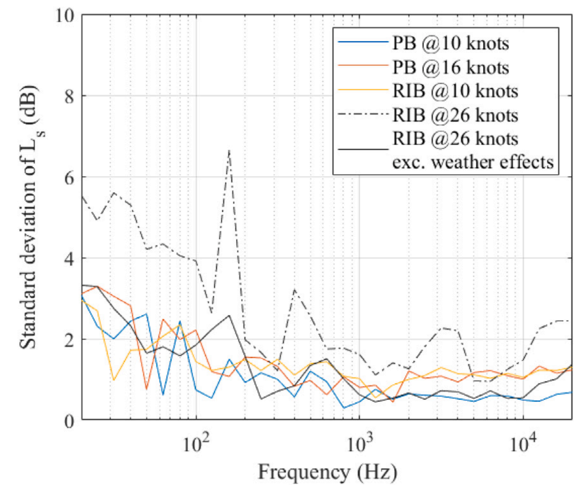


Fig. 5. Standard deviation of the decidecade source levels for selected speeds to illustrate the repeatability of the trials.

frequencies, the differences reduce further as one would expect. This suggests that a window length of 100 m is appropriate but using one much shorter than this could introduce additional error.

Another source of uncertainty comes from the weather. Even in a light sea state, small vessels are subjected to larger relative motions than large ships, leading to changes in engine and propeller loading as well as temporary changes in speed. Corrective actions may also be required to maintain heading. It is therefore reasonable to assume that the uncertainty when conducting trials for small vessels will be higher than for a large vessel in the same conditions. It was discussed in the introduction that for this trial a small sea state is desirable so that the effects can be quantified. However, given the uncertain nature of weather conditions and their effect on URN, it is worth investigating whether or not they lead to experiments which are difficult to repeat.

To demonstrate the repeatability of the experiments, the standard deviation of the source levels has been computed and a sample of these results is given in Fig. 5. This is shown for both vessels at 10 knots and their maximum speed during the trials. This shows that the uncertainty is greater at lower frequencies, as is allowed for by ISO 17208. For the pilot boat, the standard deviation is around 0.5–1.5 dB for $f > 100$ Hz and rises to a maximum of 3.3 dB at the lowest frequencies. A similar pattern is observed for the RIB at 10 knots, but not at 26 knots. At the higher speed, the uncertainty for the RIB appears much higher, peaking at 6.6 dB for f = 160 Hz. However it should be noted that, unlike for the pilot boat, these runs were conducted into and away from the prevailing weather (see Fig. 1). If this effect is removed by splitting the runs up according to heading, the uncertainty reduces considerably as can be seen in Fig. 5. This shows that the weather is a significant factor and this is considered in more detail in Section 3.4. It also suggests that the weather may only be a significant factor at higher speeds, given that the uncertainty at 10 knots is much lower despite including runs going both into and away from the weather.

Overall, once factors such as heading relative to the prevailing weather are taken into account, these results show that the uncertainty is quite low and that the trial results are repeatable.

3. Results

3.1. Source levels for the pilot boat and RIB

The overall source levels, $L_{S,OA}$, for both vessels across their speed ranges are shown in Fig. 6. These have been computed by integrating the power spectral densities over 10–20 000 Hz. For the pilot boat, the levels increase significantly across the speed range: from 156 dB at 6

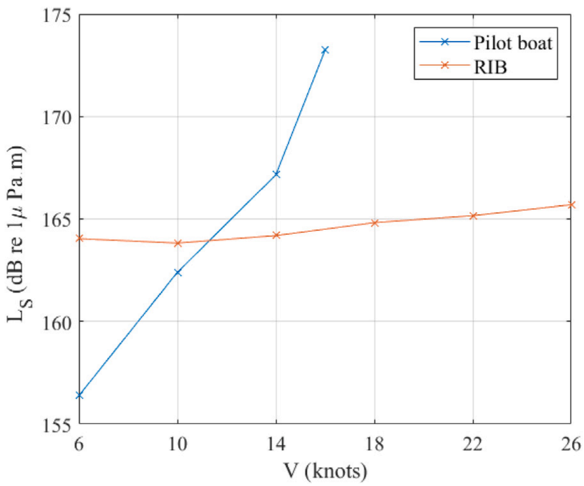


Fig. 6. Overall source levels for the pilot boat and RIB as a function of speed.

knots to 173 dB at 16 knots. This contrasts sharply with the RIB, where the source levels only increase slightly as a function of speed. The source level for the RIB varies by less than 2 dB across the entire speed range. This is unusual as vessel noise typically increases with speed, but similar behaviour has also been reported by Picciulin et al. (2022). This study found that, for a RIB of a similar size, an increase of 10 knots led to only a 2 dB increase in the source level. At its highest speed, the source level for the pilot boat is only a few dB lower than that produced by some commercial vessels with displacements exceeding 20,000 te (see table 1 in McKenna et al. (2012) for example). This shows that small vessels should not be discounted on the grounds that they are too small to be significant contributors to underwater noise levels.

Further insights can be gained by looking at the decidecade band data for the two vessels, shown in Fig. 7. The source levels for the pilot boat are dominated by low frequency sound. The increase in the frequency of the dominant sources at $60 \leq f \leq 100$ Hz is due to the increasing shaft speed of the vessel. This is examined further in Section 3.2. There is also a significant increase in broadband noise at higher frequencies. The relationship between the speed and source levels is more nuanced for the RIB. The low frequency noise associated with the engine and propeller does not notably increase as function of speed. There is a notable component at 4 kHz that does increase with speed, although it never dominates the source level.

For both vessels, the lower frequency noise ($f \leq 1$ kHz) consists primarily of tonal noise associated with the engine and propeller frequencies, and this is analysed in more detail in the next section. The higher frequency noise ($f > 1$ kHz) is more difficult to attribute to one particular source, as it is primarily broadband and can be made up of many different components including flow noise, cavitation, and spray. However, one can gain some insight into the make-up of this noise by considering how it changes with speed. Flow noise due to vortex shedding off the hull, rudders, struts and other appendages is typically assumed to scale according to

$$\bar{p}_a^2 \propto V^6 \tag{16}$$

where $\bar{p}_a^2$ is the mean square of the acoustic pressure and V is the speed of the vessel. This relationship can be derived from first principles by considering the pressure fluctuations on a body induced by vortices as they shed from it (Blake, 2017a,b). Experimental studies have also suggested that broadband cavitation noise can be scaled according to a power law, for example MacGillivray and De Jong (2021). An exponent of 6 is sometimes proposed for this, usually referencing the work of Ross (1979). However due to difficulties in isolating noise sources, non-cavitating and cavitating broadband noise sources are seldom separated. As a result, any particular dataset to which a power law is fitted will likely contain both assuming the vessel is above its cavitation inception speed. More recent analysis of full-scale measurements of large vessels by MacGillivray et al. (2019) suggests that different exponents may be more appropriate for different vessel types and speeds. No such data is available for small craft at the time of writing. It should also be noted that such laws assume that the vessel is cavitating at all of the speeds under consideration. If the speed range under consideration contains speeds where cavitation is not present or very minimal, then any power law is unlikely to provide a good description of the scaling with speed.

Fig. 8 shows how the higher frequency noise varies with speed for both vessels. A V^6 reference line is shown in both cases and it is clear that the high frequency noise from the pilot boat follows this scaling law closely across the entire speed range. Given that this scaling is present at low speeds as well as higher speeds, it is likely that flow noise is an important part of this. Further research, including visualisation of the flow around the propeller, is needed to provide a more conclusive breakdown of this high frequency noise in terms of cavitating and non-cavitating components. This will also aid the development of scaling laws for small craft noise. The high frequency RIB noise does not scale with this power law, or indeed any power law. At some frequencies it remains fairly constant across the speed range, only increasing at the higher speeds, with the exception of the 4 kHz component, which does increase significantly with speed as noted earlier. This still does not increase according to a power law though, and so we cannot attribute it to either fluid-induced noise or cavitation without further research. The differences between the vessels are perhaps not surprising given their different hullforms and appendages. The pilot boat has a rudder, keel and struts, the flow over which would be expected to produce noise that scales in this manner. The RIB has none of these features and any non-cavitating flow noise is likely due to turbulent fluctuations in the boundary layer and spray. Sound levels from these phenomena do not have a straightforward relationship with speed and so it is difficult to elucidate on this further.

3.2. Narrowband analysis

Narrowband analysis has been performed for both vessels for frequencies up to 1 kHz. This is shown in Fig. 9 for the pilot boat at 10 knots and 16 knots and in Fig. 10 for the RIB at 10 knots and 26 knots. A bin width of 1 Hz is used in these figures. The cylinder and engine firing rates and blade passing frequencies have been determined from the shaft speeds recorded during each trial, and these values have been compared to the tonal peaks for both vessels. Due to the propulsion arrangement for the pilot boat, the propeller blade rate (denoted B) is equal to the engine firing rate (E). This leads to a series of prominent, equally spaced tonal components at multiples of the cylinder firing rate (C) because $E_i = B_i = 4C_i$ for the ith harmonic. At both speeds, every prominent tonal component in the spectrum lines up with the cylinder firing harmonics, which shows that the low frequency noise is almost completely due to the cylinder firing processes and the blade rate harmonics. These components all increase with speed, and given their continued importance (particularly C1), the results indicate that the engine noise is significant at both speeds. Unfortunately, due to the matching of the engine and propeller frequencies, it has not been possible to determine how much of the increase in the E and B components is due to the propeller. Having a propulsion system where the engine and propeller frequency components match up like this should be avoided because it leads to the high amplitude tonal components that are seen in Fig. 9. Design practice for larger vessels would normally ensure this does not happen, but this shows that such guidance is not always followed for smaller vessels, where sound and vibration are seldom prioritised.

For the RIB, the low frequency noise is dominated by the engine at both low speeds and high speeds. Noise at the propeller blade rate

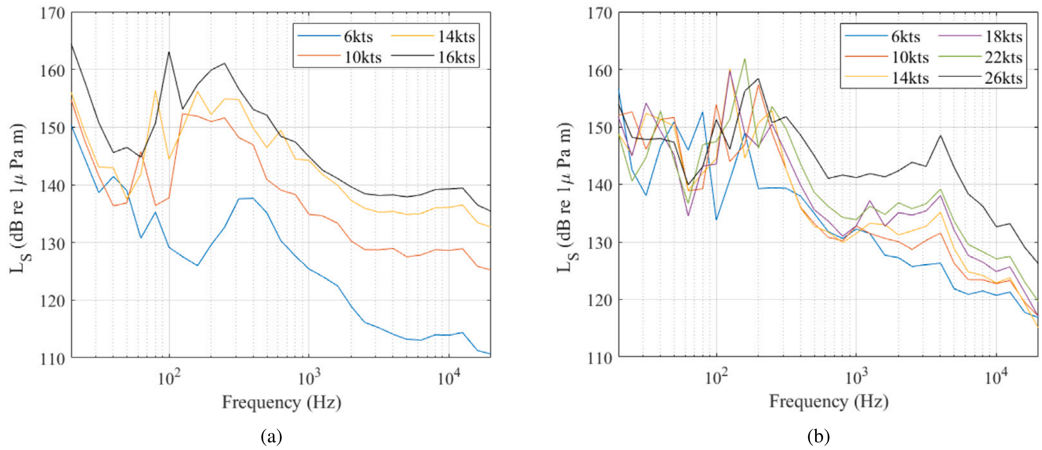


Fig. 7. Decidecade band source levels for (a) pilot boat and (b) RIB at multiple speeds.

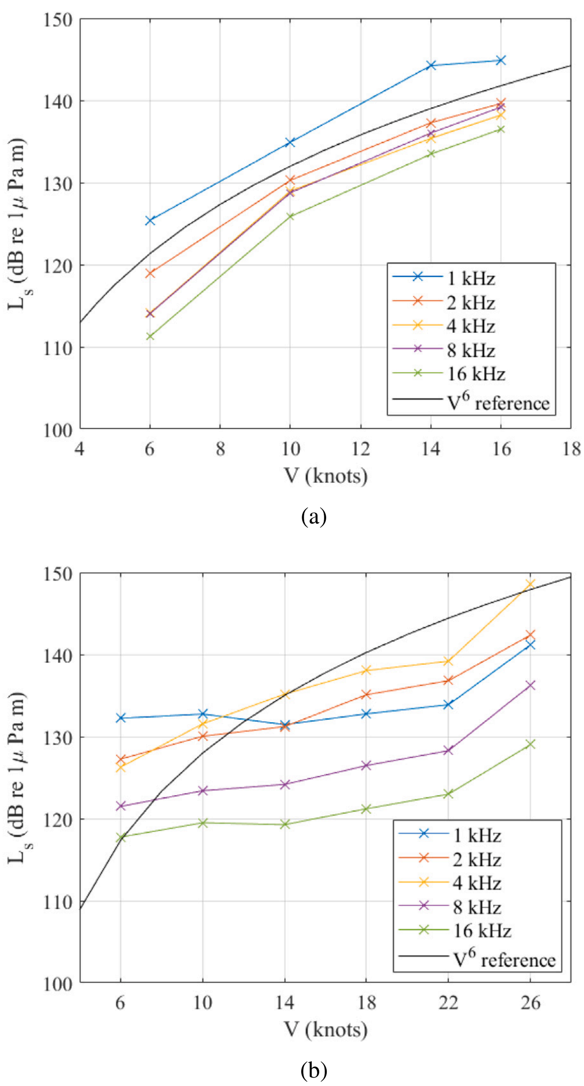


Fig. 8. Selected decidecade bands as a function of speed for (a) pilot boat and (b) RIB. V^6 reference lines are shown for comparison.

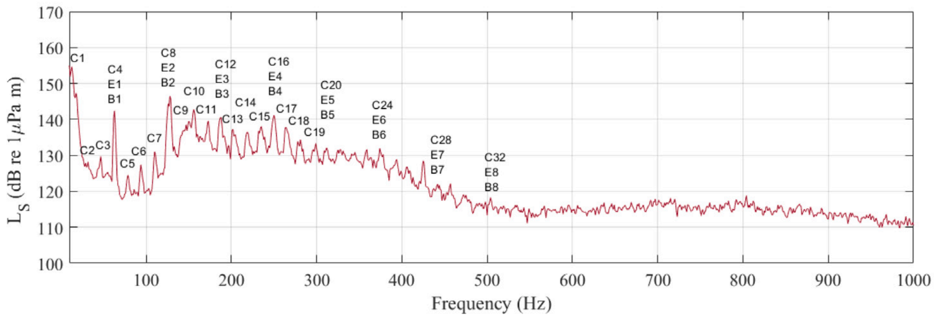
harmonics does increase from 10 knots to 26 knots (particularly B1 and B2), but the engine is the dominant source noise here. This is interesting because we typically assume that engine noise only dominates at low speed. However, the propeller on a RIB operates in quite a different flow regime than for the pilot boat or other larger vessels. The main spatial variations in the wake are the result of the strut on the engine and flow over the bottom of the hull. Therefore, the spatial variations that lead to prominent blade rate harmonics are reduced for the RIB and this helps to explain why this component is lower, even at higher speeds. This also explains why only the first few blade rate harmonics can be identified in the spectrum. These figures also show that many narrowband components of the noise do increase with speed. However, because the signature is dominated by only a few tones which increase only very slightly from 10 to 26 knots, the overall level only increases by a small amount.

3.3. Effect of source depth and running attitude

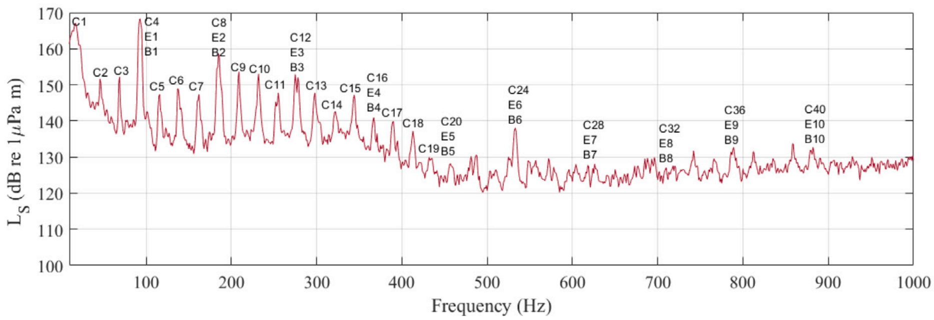
The relative invariance of the RIB source level to changes in speed masks something important when considering how the noise propagates away from the source. In Section 2.3, it was shown that the propagation loss is frequency dependent, with lower frequencies attenuating more rapidly than higher frequencies. It was further shown that this is primarily due to the Lloyd's Mirror effect, which is significant due to the close proximity of the source terms to the free surface. The corollary of this is that the low frequency noise associated with the propeller and engine decays rapidly, and the noise level becomes increasingly dominated by the higher frequency broadband noise.

This effect can be seen in Fig. 11, which shows the source levels and received levels (at array 1) for the RIB at 10, 18, and 26 knots. The low frequency tonal noise associated with the engine dominates the source levels, and this is relatively invariant with speed. However, the high frequency noise shows a strong dependency on speed, and because this decays less than the engine noise, it comes to dominate the acoustic far-field at higher speeds. The end result is that, despite the overall source level only increasing 1.9 dB from 10 to 26 knots, the received level increases by 11.0 dB. This is an important result when one is considering the effect of vessel noise on marine ecosystems: namely that the source level tells us only half the story. When using such information, one must be careful to correctly account for the source depth in any propagation modelling or risk misinterpreting the acoustical impact such a vessel might be having.

The result that the source levels for the engine noise do not increase significantly with speed warrants further investigation, as anyone who has been on a RIB will attest to the fact the airborne noise from the engine does increase with speed. To help understand this, vibration

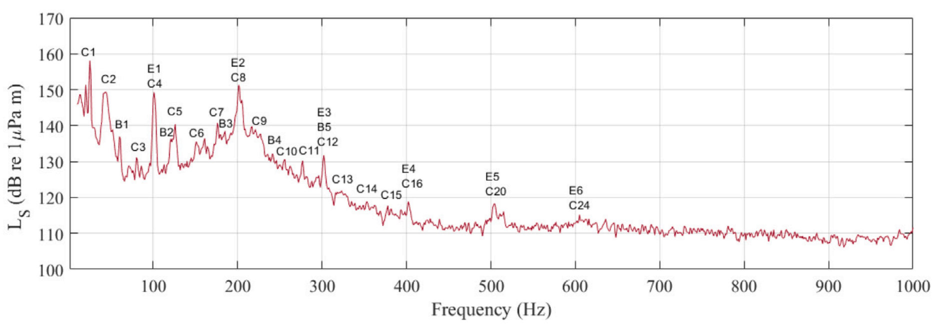


(a)

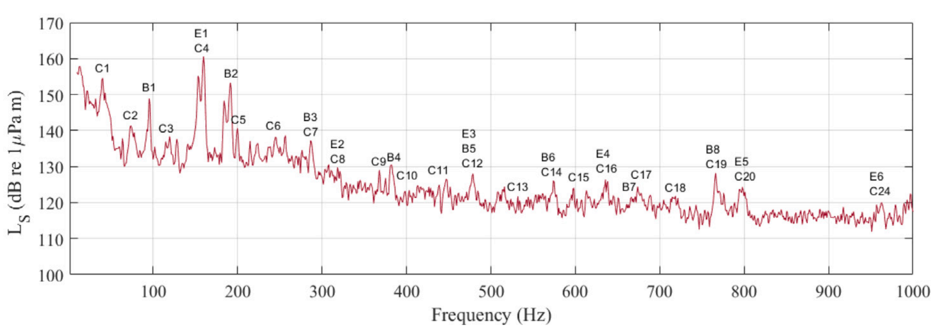


(b)

Fig. 9. Narrowband acoustic spectra for the pilot boat at (a) 10 knots and (b) 16 knots. The cylinder firing rate harmonics are denoted *C*, engine firing rate *E*, and propeller blade rate *B*.



(a)



(b)

Fig. 10. Narrowband acoustic spectra for the RIB at (a) 10 knots and (b) 26 knots. The cylinder firing rate harmonics are denoted *C*, engine firing rate *E*, and propeller blade rate *B*.

data are presented in Fig. 12. This shows the decidecade band vibration levels measured on the inside of the hull. The figure clearly shows a significant rise in vibration levels at all measured frequencies as the speed increases, something that is not reflected in the acoustic data. The increase is greatest between 6 knots and 14 knots, with lower increases at higher speeds.

Narrowband vibration data, presented in Fig. 13 for 10, 18 and 26 knots, provide further insight. Increases in vibration levels at low frequencies are clearly evident, and many of these are at cylinder and engine firing rate harmonics. Secondly, there is a clear broadband hump between 500 and 600 Hz that becomes very prominent at higher speeds. This component is not seen in any of the acoustical data, and it

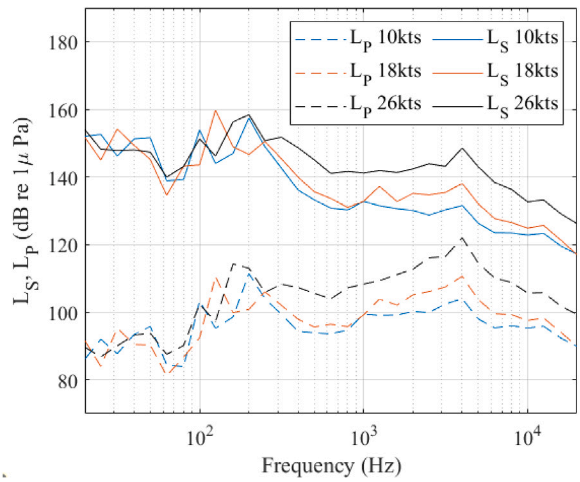


Fig. 11. Source levels and received levels for the RIB at 10, 18 and 26 knots.

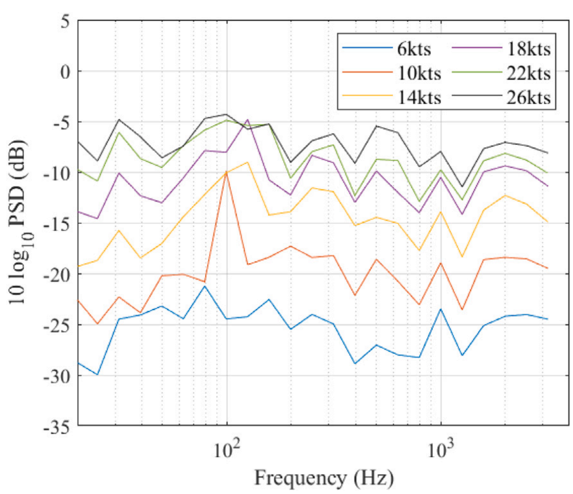


Fig. 12. Power spectral densities of the vibration levels (measured as vertical acceleration) inside the hull on the RIB.

is not clear what the origin of this is. Irrespective of these unknown components, there is a clear increase in vibration levels associated with the engine that do not translate into increases in the underwater radiated noise.

To understand why this happens, we must look at the running attitude of the vessel. The RIB is a planing vessel, and at 6 knots it has a Froude number of $F_n = 0.39$. The Froude number is defined as $F_n = V_m/\sqrt{gL_{wl}}$ where V_m is the vessel speed in m s^{-1}, $g = 9.81$ m s^{-2} is the acceleration due to gravity and L_{wl} is the waterline length. At this Froude number, the dynamic sinkage tends to be close to its maximum, and above this the vessel begins to lift out of the water before planing at around $F_n \approx 1.0$ (Molland et al., 2017). This corresponds to a speed of 15.5 knots for this vessel. The resistance typically rises sharply for $0.3 \leq F_n \leq 0.6$, leading to increases in propeller and engine loading which explains the sharp increase in vibration levels at these speeds. The rate of increase then tends to drop off as the vessel starts to plane, and the vibration data again mirrors this.

There are two reasons why these increases do not translate into increases in underwater noise. The first is the Lloyd's Mirror effect. As the vessel lifts out of the water, the propeller and the submerged part of the outboard engine move closer to the free surface. In Section 2.3 it was shown that reducing the source depth leads to increased propagation losses and so as the vessel lifts out of the water, this effect becomes greater. Secondly, the hull is responsible for radiating some of the engine noise, and so this lifting out of the water reduces the transmission of the vibration into the water. Therefore, the percentage of the vibration that results in far-field noise decreases as the vessel goes faster. The result of this is the large increases in vibration levels in the hull are, in a large part, offset by the changes in the hydrodynamics that lead to the vessel lifting out of the water as the speed increases. This effect is likely to be very dependent on the vessel displacement, length, hull design and speed as well as the prevailing weather conditions which all influence the running attitude. This result cannot be transferred easily to other vessel types, but it provides an explanation of a phenomenon that has been reported by other studies of RIBs (Erbe et al., 2016; Picciulin et al., 2022).

The pilot boat on the other hand is larger and has a maximum speed of 16 knots. It is designed as a semi-displacement vessel and has a Froude number of $F_n = 0.85$ at its maximum speed. At this speed, it does plane in calm water but a larger proportion of the hull remains in the water than for the RIB. The twin propellers operate in flow with a much higher spatial variability, and there is a much larger wetted surface area to enable vibration from the engines to be radiated into the water. This explains why the same behaviour is not seen for this vessel and instead the radiated noise levels increase substantially with speed.

3.4. Effect of weather

When conducting trials to obtain 1 m equivalent source levels, it is usually better to conduct them in calm weather to enable consistent, inter-comparable data to be obtained. In ISO17208-1 (2016), it is stated that the wind speed during trials should be less than 20 knots, although it is acknowledged that calmer conditions may be required for smaller vessels. However, it is of interest to understand what the effect of weather is on the underwater noise from marine vessels given that they spend much of their time not in perfectly calm conditions.

As discussed in Section 2.1, these trials were carried out in weather conditions that are acceptable for ISO17208-1 (2016), but the conditions are still significant for small vessels, particularly those with low displacements such as RIBs. Wave-induced motions cause temporary changes in engine loading and change the local flow around the propeller, which in turn changes the propeller loading. As a vessel heaves and pitches, the source positions change relative to the local free surface and more or less of the hull may be in contact with the water, causing more or less of the vibration to transmit into the water as noise. These effects all cause temporary changes in the radiated noise. Motions can also be a direct source of noise, for example slamming. Slamming can occur when the vessel lifts out of the water and then "slams" back down creating a transient pressure pulse on the hull. The strength of this depends on the hullform geometry, with lower deadrise angles leading to higher slam pressures, and the effect can be made worse if air is trapped under the hull as it re-enters the water (Kapsenberg, 2011).

To investigate the influence of motions on the radiated noise levels, spectrograms have been computed for both vessels at two speeds. These are shown in Figs. 14 and 15. For the pilot boat, a number of slam events can be identified as transient broadband spikes, primarily at low frequencies. These events have been confirmed by comparing with vibration data at the same times. Slam events typically become more frequent and severe at higher speeds, and this can be seen when comparing figures (a) and (b) in Fig. 14. In fact, at 16 knots some slam events produce noise at levels that exceed those from the engines and propellers. Amplitude variation can also be seen in these spectrograms, particularly at the tonal frequencies at the engine firing rates and blade rates. The time period of these variations is of the order of seconds, corresponding to heave, pitch, and roll motions that cause variations in engine and propeller loading as well as to the transmission of the noise into the water.

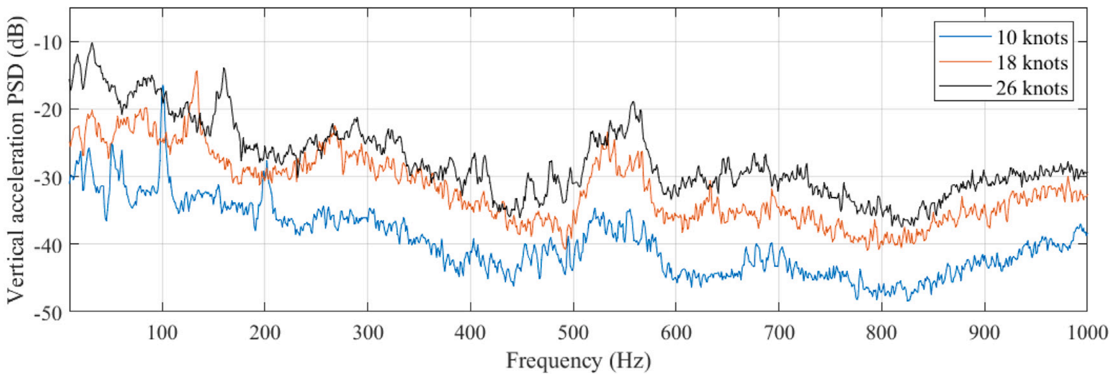
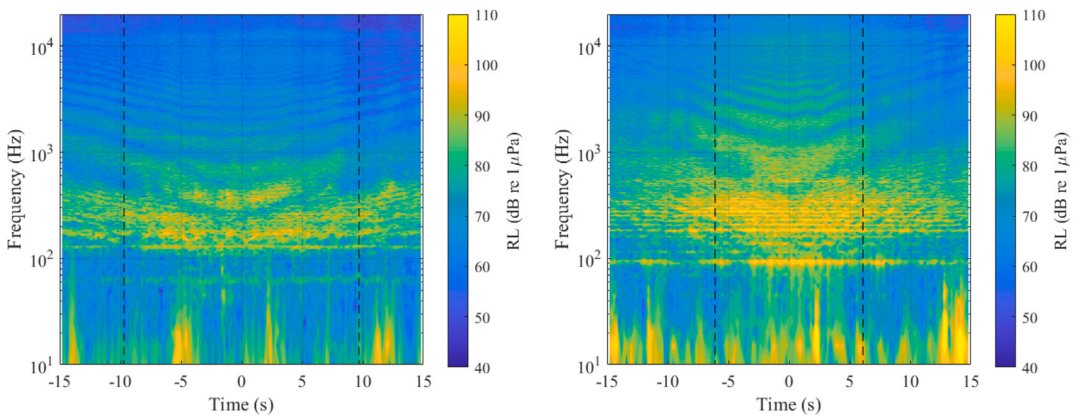
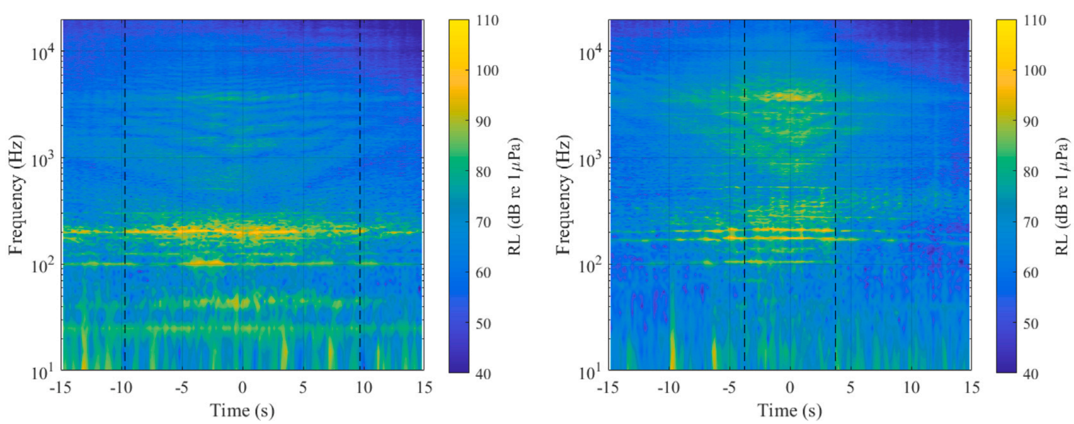


Fig. 13. Narrowband spectra the of the vertical acceleration on the hull of the RIB from 10 to 1000 Hz for the RIB at 10, 18 and 26 knots.



(a) (b)

Fig. 14. Spectrograms for the pilot boat at (a) 10 knots and (b) 16 knots. The frequency resolution is 5 Hz and the temporal resolution is 0.2 s. Time = 0 s corresponds to the closest point of approach. The data window lengths are shown with dashed lines.



(a) (b)

Fig. 15. Spectrograms for the RIB at (a) 10 knots and (b) 26 knots. The frequency resolution is 5 Hz and the temporal resolution is 0.2 s. The data window lengths are shown with dashed lines.

A similar pattern is seen for the RIB in Fig. 15. Here, the intermittency appears to be more significant at higher speeds. This again helps to explain why the noise levels do not increase with speed, despite significant increases in onboard vibration. Some slam events can be seen here, but their amplitude is far less than for the pilot boat. The principle reason for this is the displacement mass of the RIB is much less, reducing the slamming pressures and subsequent noise.

The vessel's heading relative to the prevailing weather is also of interest. Trials carried out for the RIB were done in conditions close to head waves and following waves, allowing for the effect of this on the radiated noise levels to be captured. The overall sound level as a function of both speed and heading is shown in Fig. 16. This shows that for lower speeds there is very little difference in the source level as a function of heading. However, there is sharp change between 14 and 18 knots, with the source levels increasing when in head seas, but dropping in following seas. These changes are more significant than those caused by changes in speed, which highlights the importance of taking such effects into account.

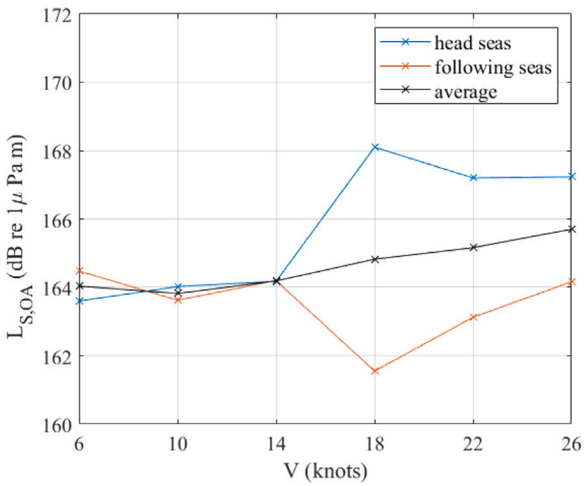


Fig. 16. Overall sound level for the RIB in head seas and following seas.

To explain this behaviour, we must again consider the running attitude of the vessel. It was shown in Section 3.3 that the vessel starts to fully plane at around 15–16 knots, and the change in behaviour shown in Fig. 16 coincides with this speed. This points to the running attitude being of interest, but before we can make such an attribution, it is necessary to consider both the acoustic and vibration data at 14 and 18 knots in head and following seas. This is shown in Fig. 17.

These figures tell us several things. Firstly, a reduction in vibration levels is seen at both speeds when going from head seas to following seas. This confirms that the effect illustrated in Fig. 16 is not one of directionality. In other words, it is not due to the vessel passing the hydrophones on the starboard rather than the port side. Both graphs show a reduction in the source level, but the effect is clearly larger at 18 knots. At 14 knots, reductions are observed at some frequencies but the dominant components at 125 Hz and 250 Hz are very similar, leading to very little change in the overall level. At 18 knots there is a more substantial drop in noise including at the dominant frequencies, leading to a reduction in the overall level. The vibration data show similar behaviour at both speeds. There is a reduction in vibration at all frequencies below 1 kHz, with similar reductions observed at both speeds. This suggests that the vibration induced by the engine reduces at both speeds when going to head to following seas, but this only translates into a significant reduction in noise at 18 knots and above. This points towards a relationship between the vibration, radiated noise, and the vessel attitude when in head or following seas. Further trials across a broader range of weather conditions and headings are needed to confirm this relationship and understand how the running attitude and motions at different relative headings affects how much noise is radiated into the water.

4. Conclusions

This paper has presented results from acoustic trials carried out on two small vessels: a pilot boat and a RIB, in a range of conditions. Hydrophones located at two distances from the closest point of approach have enabled different analytical approaches for propagation losses to be assessed for trials conducted in shallow water. For these trials the Lloyd's Mirror effect is the most important factor to consider due to the close proximity of the sources to the free surface. This leads to increased propagation losses at low frequencies, with the effect becoming more significant the closer the source is to the free surface. A soft seabed made up of water-saturated sand and mud minimised the reflections, and comparisons between experimental data and the analytical methods confirmed that seabed effects were small.

The source levels for the pilot boat increased significantly across the assessed speed range (6–16 knots), whereas the levels for the RIB remained roughly constant across a broader range (6–26 knots). The results show very different patterns for the two vessels, with their different propulsion architectures and running attitudes being the dominant factors. The RIB source level was shown to be dominated by engine noise across the speed range, but due to the higher propagation losses of the lower frequency noise, it was shown that higher frequency noise dominated the far field at the highest speeds. Vibration levels measured on the hull do increase with speed, and a large proportion of this vibration was found to be attributable to the engine. The fact that this does not lead to a significant increase in URN points to a reduction in the transmission efficiency of the vibration into radiated noise, which can be explained by the running attitude of the vessel. As it speeds up, the RIB lifts out of the water and starts planing. Therefore, the proportion of the hull and engine in the water decreases, reducing the amount of noise transmitted into the water. These results highlight the importance of running attitude for semi-displacement and planing craft, with this complicating the relationship between speed and radiated noise levels. Computational studies would be useful here to understand this effect in more detail.

For both vessels, the engine noise was prominent at all speeds. This differs from many studies of larger vessels, which tend to become dominated by propeller and cavitation noise at higher speeds, with the engines only dominating at low speeds. Therefore from a design perspective, engine selection and design and the use of mounts to reduce vibration transmission should be given greater attention for these vessels in order to reduce the impact they have on the underwater soundscape. Higher frequency noise was found to scale with V^6 across the entire speed range for the pilot boat, and while this increased significantly over the speed range it never exceeded the low frequency noise from the engine. It was more challenging to determine the origins much of RIB noise above 1 kHz, and further work is needed to try and quantify sources such as cavitation, spray, and flow noise here.

The vibration measurements have provided important insights into the relationship between onboard vibration and underwater radiated noise, particularly as a function of speed, running attitude and heading relative to the prevailing weather. However, given the complex relationship between onboard vibration and URN, it is difficult to draw more general conclusions about how these two relate for small vessels. The vibration characteristics of a vessel are functions of propulsion architecture, displacement, structural design, materials, and the construction methods used, and so significant variations are likely across different small vessel types. However, when used as a relative measure of vibration and in conjunction with URN measurements, this study has shown that such measurements are valuable. Additional measurements made across a broader range of small vessels may yield more definite relationships that could ultimately allow onboard measurements to serve as a proxy for underwater radiated noise.

Weather effects were examined and it was shown that slamming can be a significant source of noise, but its short duration limits the overall impact. The RIB source level was shown to be strongly dependent on the heading relative to the prevailing weather, but only at higher speeds. Analysis suggests that this is linked to whether or not the vessel is planing, but further trials are needed to confirm this and to better understand how weather affects the radiated noise levels. Future studies should measure the loading on the engine alongside more comprehensive vibration measurements. This should be combined with measurements of the vessel motions to provide a comprehensive understanding of how weather and heading influences the onboard vibration and radiated noise levels. Future studies should also attempt to visualise the cavitation of the propeller at different speeds and in different weather conditions to provide better insights into how this influences the radiated noise levels.

The differences in the acoustic characteristics of the two vessels make it difficult to draw general conclusions about the nature of small

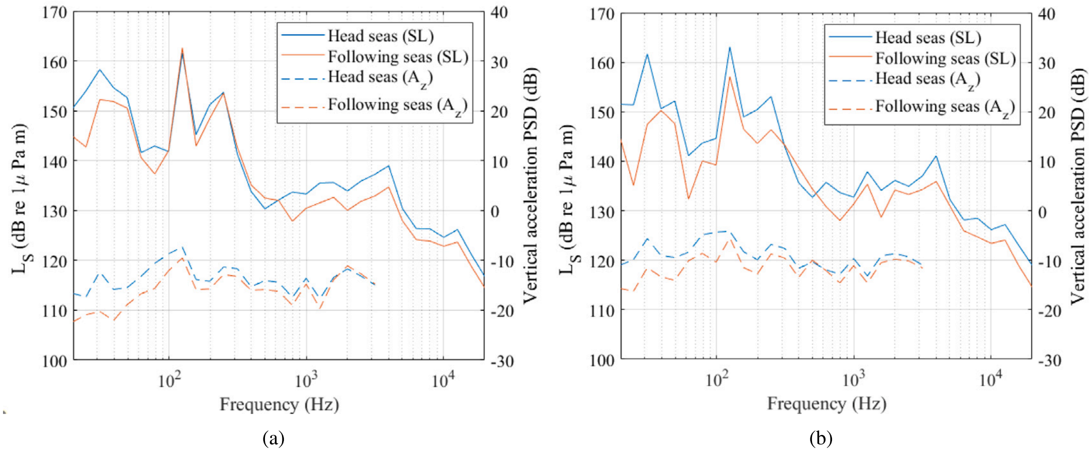


Fig. 17. Change in sound and vibration levels when going from head seas to following seas at (a) 14 knots and (b) 18 knots. The solid lines denote noise levels (left axis) and the dashed lines denote vibration (right axis).

boat noise. Given the results presented here, it is likely that differences in propulsion architecture and running attitude are key factors, and these vary widely across small vessel designs. The pilot boat signature was, in many ways, not dissimilar to that of a larger commercial vessel. The source level increased with speed and was dominated by low frequency noise associated with the engine and propeller. Higher frequency flow noise increased with speed in a predictable manner. The RIB is a lightweight, outboard powered craft with a variable running attitude depending on the speed. The acoustic characteristics of this vessel do not agree with larger vessels, or indeed with the pilot boat. In summary, the data presented here suggest that small boat cannot be considered as a homogeneous vessel class when considering their impact on underwater noise levels. Instead, a more nuanced characterisation is required that reflects the very broad range of vessels that are considered "small craft".

CRediT authorship contribution statement

Tom A. Smith: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea Grech La Rosa:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Bill Wood:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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