Research Paper

Field Study on Underwater Noise Emitted by Small Tourist Boats. Comparison Between the Use of Electric and Combustion Motors

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Small boats, possessing outboard engines, are widely used in tourism and mammal watching within marine protected areas. Noise generated by this type of vessels has the capacity to negatively affect marine fauna, especially marine mammals, which use sound throughout all the phases of their lives. These tourism boats used in mammal watching may use different propulsion systems, such as gas, diesel or electric engines. To characterize underwater noise emitted by this type of vessels becomes relevant not only when assessing the acoustic impact produced by these different propulsion systems over the marine fauna living inside these protected marine areas, but also when determining which one produces the least impact. A comparative study of underwater noise emissions coming from small touristic boats was made in this study. Boats were similar in capacity and functions, although possessing different propulsion systems. Measurements were made on two boats with a 50 Hp internal combustion engine and one 5 Hp electric boat. These boats were selected to be studied because they have practically the same size, possess the same passenger-capacity and are used to make similar jobs and routes inside the protected area where they are operated. The electric boat showed a considerable decrease in underwater noise emissions, especially in low frequencies. This boat will produce a lower accumulated exposition of the fauna to the noise or will allow a closer approach to the observed species. Measurements were made between September 2018 and January 2020.

Keywords: small boat underwater noise; anthropogenic underwater noise; electric motor boat; internal combustion engine boat; underwater noise produced by tourist boats.

1. Introduction

From all the different types of existing anthropogenic underwater noise, the most commonly found worldwide is that produced by vessels, which has the potential to negatively affect marine organisms. In Europe, efforts to monitor and manage acoustic contamination by vessels are included in the Marine Strategy Framework Directive, MSFD, and its descriptor 11.2 (Commission of the European Communities, 2008), which forces member states to guarantee that underwater noise levels will not exceed those thresholds that endanger the Good Environmental Status (GES) of EU waters (European Commission, 2017).

Underwater noise emitted by a vessel mainly depends on its size, on the engine power and on its speed (GRELOWSKA *et al.*, 2013; SANTOS-DOMÍNGUEZ *et al.*, 2016; KLAUSON, MUSTONEN, 2017). Vessels possess different types of noise sources, where the relative acoustic intensity emitted by these noise sources depends on the type of vessel and their velocity (ABRAHAMSEN, 2012).

In Valdivia, a city located in the south of Chile, in South America, there is an estuary and a marine protected area inside this estuary, very much visited by tourists, mainly through small boats powered by internal combustion outboard engines. This type of boat is the most commonly used inside Chilean marine protected areas, where touristic activities of marine mammal watching are carried out. Boats powered by electric motors were included in this activity. The goal of introducing this type of motors was to use touristic boats more friendly towards the environment, thus diminishing water contamination by wastes left by internal combustion engines and airborne noise emissions, which have almost completely disappeared with this type of motor. Regarding underwater noise emissions, the answer whether a boat with an electric motor is more silent than another similar boat with an internal combustion engine is not simple.

As small boats, with passenger capacity between 10 and 20 persons, are widely used in tourism and mammal watching within Chilean marine protected areas, to characterize the underwater noise produced by this type of boats is very important for the evaluation of the impact that the different types of vessels may produce over the marine fauna existing inside these marine protected areas.

There is little available information on the underwater noise level emitted by small boats as well as on the difference in the noise level emitted by the different types of engines used by small boats, such as electric motors and internal combustion engines.

Due to the above, it was established as an objective for this work to carry out a comparative study of underwater noise emissions, generated by small tourist boats with different propulsion systems. Two boats with an internal combustion engine and one with an electric motor were subjected to studies. Through the results of this noise emissions study, decisions on the type of vessel that should be used in marine mammal watching tourism in marine protected areas can be made.

These three boats were chosen for this study since they are considered as similar and appropriate to be compared. This is because they have almost the same size, bearing the same passengers capacity and are used to perform similar routes and duties inside the estuary. The Chilean Navy Port Authorities classify these three vessels as "small". Worth remembering is that the efficiency of internal combustion engines is under 50%, whereas that of an electric engine is about 90% (Ekdahl Espinoza, 2014).

2. Underwater noise impact

Anthropogenic underwater noise has increased its presence in the oceans and coasts due to intensification in human activity (Andrew *et al.*, 2022; McDonald *et al.*, 2006; Ross, 2005), thus increasing existing concern about its impact over marine life (Tyack, 2008; Kunc *et al.*, 2016).

Marine mammals have evolved exploiting water capacity to transmit sound waves through long distances and with low absorption. This efficiency is not the same for electromagnetic waves such as light, which are rapidly attenuated (Grelowska, Kozaczka, 2014; Urick, 1996; Kinsler *et al.*, 1999). This is why marine mammals, especially cetaceans, use mainly sound, more than any other signal to perceive their surrounding and interact with it (Tavolga, 1965; 1971; Hawkins, Myrberg, 1983).

Marine mammals use principally their auditory system for sailing, feeding, distance calculation, communicating, hunting, socializing, etc., since this is their sense possessing a broader range (Richardson *et al.*, 1995; Tyack, 2000).

This is why noise generated by human beings under the water has the capacity to negatively affect marine fauna, especially cetaceans, which use sound throughout their life phases. These negative effects can range from physiological stress, behavior changes, masking, temporal hearing loss, permanent hearing loss and death (McCauley *et al.*, 2003; Wysocki *et al.*, 2006; Wright *et al.*, 2007). A little longer than a decade ago, the first scientific guide about maximum limits of underwater noise exposition was published; it was targeted at avoiding the occurrence of hearing impairment, both temporal (TTS) and permanent (PTS) as well, in marine animals exposed to it (Southall *et al.*, 2007). Other new guides have been updating these exposition limits according to advances in research about noise impact on marine mammals (National Marine Fisheries Service [NMFS], 2016; 2018; Erbe *et al.*, 2016).

3. Noise sources in vessels

Noise sources in ships may be grouped into three categories: machinery noise, propeller noise and hydrodynamic noise (Urick, 1996).

Machinery noise is originated as a mechanical vibration of the different parts of the propulsion system and auxiliary machinery of a ship, which is transmitted to water through the hull. This type of noise is present in ships with rigid mount diesel engines and are originated in hydraulic systems, compressors, generators, shafts and gears, which transmit not only their vibration, but also their airborne noise transmitted to the environment through the ship hull. This type of rotary motion machine with a determined number of revolutions per minutes (rpm) produces a noise spectrum dominated by tonal components of the fundamental frequency and harmonics corresponding to rpm of the rotary movements of machines.

The main source of propeller noise is the cavitation noise induced by the propeller rotation. When the propeller rotates in the water, areas of low pressure are generated, both at the tip and on the surface of the propeller blade. If this negative pressure is low enough, a change in the water phase is produced, thus generating hundreds of tiny air bubbles, which rapidly implode or collapse after moving away and due to high increase in pressure, hence generating a strong impulsive noise.

Consisting of a big number of random implosions produced by the collapse of gas bubbles, the cavitation noise possesses a uniform frequency spectrum. The spectrum (due to the propeller cavitation) has a negative slope in high frequencies of −6 dB/octave and a positive slope of 6 dB/octave in low frequencies. There is a peak in the spectrum located between 100 Hz and 1000 Hz for big vessels. The peak amplitude and its position in the frequency axis change with the vessel velocity. The spectrum amplitude increases as velocity increases; whereas the peak frequency decreases as velocity increases. There is a velocity from which the phenomenon of cavitation starts. The level of cavitation noise increases from this critical velocity.

Moreover, the passage of water through the propeller produces a propeller noise composed by tonal components of low frequency, which add to the uniform spectrum of the cavitation noise. These components coincide with the propeller turning ratio and are originated by the propeller resonance, excited by the vortices shedding from it.

Finally, hydrodynamic noise is produced by the irregularity and fluctuation of the flow along the hull as a result of the movement of the ship. Pressure fluctuations produced by this irregular flow are radiated as noise. This noise is also known as flow noise. Under normal circumstances of operation and design, hydrodynamic noise has little contribution to the total noise irradiated by vessels, since the most probable fact is that this noise is masked by the machinery noise and propeller noise.

The vessels in this study are small boats used for tourism and mammal watching. These boats have thin, narrow hulls with no protruding appendages from the hull, so their main source of underwater noise is the noise produced by the propeller.

4. Method

4.1. Measuring system

The system used to measure the noise emitted by the boats consists of the hydrophone Cetacean Research model C55/736 with a lineal response from 0.15 Hz to 44 kHz and the digital recorder Tascam DR680MKII possessing quantization rates, Q: 16/24 bit and sampling frequencies, fs: 48/96/192 kHz, which are used to record noise emissions. Afterwards, sound files are loaded to the software SpectraPLUS-SC 5.1D, where the required noise descriptors are obtained. A sampling frequency of 48 kHz was used in this study.

Due to the lack of facilities to carry out the calibration of the system under water, the system was calibrated inside an anechoic chamber following the steps indicated in the standard EN 60565 (2007) which allows calibration in air and in free field conditions, replacing the reference hydrophone with a calibrated microphone. A sensitivity of −167 dB re.1V/μPa for the hydrophone and a sensitivity equal to −154.9 dB re.1V/μPa for the system hydrophone plus recorder were obtained with the standard. The software SpectraPLUS-SC5.1D was calibrated using this last sensitivity and a pure tone of 400 Hz.

The process was made inside the anechoic room of the Acoustic Department from Universidad Austral de Chile, whose dimensions are 2.45 m wide, 4.45 m long, and 3.8 m high, with a chamber cut-off frequency of 120 Hz and a wedge cutoff frequency equal to 170 Hz.

The complete system consists of a hydrophone, a buoy, a recorder and a kayak as means of transport. The hydrophone and its buoy are deployed from the kayak.

4.2. Vessels evaluated in the study

To carry out comparisons of underwater noise emissions produced by small touristic boats with different types of propulsion, two boats with internal combustion outboard engine and one boat with solar-powered electric inboard motor were used.

These types of boats were chosen because in the marine protected areas, where touristic watching activities are made, internal combustion outboard engine boats are the most widely used. The motivation to include boats with electric engines was to know how much more friendly they are with the environment, when contrasted with those using internal combustion engines.

4.2.1. Internal combustion outboard engine boats

Boats belonging to this type were identified as "combustion motor boat 1" and "combustion motor boat 2". Figures 1 and 2 show these boats, respectively. Table 1 shows the characteristics of these vessels.

Fig. 1. Combustion motor boat 1.

Fig. 2. Combustion motor boat 2.

Table 1. Characteristics of evaluated boats.

Name	Length [m]	Motor	Power [Hp]	Passengers	Size*
Combustion motor boat 1	9.5	Internal combustion/Outboard	50	16	small
Combustion motor boat 2	8.2	Internal combustion/Outboard	50	12	small
Electric motor boat	9.5	Electric/Inboard	5	16	small

*According to classifications by the Chilean army.

These two boats are used for touristic rides inside the estuary of the Valdivia River. They are also used for touristic routes inside a marine protected area known as "Nature Sanctuary of Cruces River" (Ministerio del Medio Ambiente, 2015; Ministerio de Educación Publica, 1981). These two boats represent all touristic vessels of the estuary, listed as small by the Port Authority of Valdivia, belonging to the Chilean Navy.

4.2.2. Solar-powered electric motor boat

This type of vessel was introduced in 2012; the goal was to implement a sustainable river transport system in the rivers of the estuary. Contrasted with their competitors, these boats are recognized as more friendly with the environment, since they do not produce contamination by wastes, as do boats powered by internal combustion engines. The assessed boat of this type, identified as electric motor boat, has the same touristic route as that of combustion motor boats 1 and 2. Figure 3 shows the assessed electric boat and Table 1 shows its characteristics. We must remember that the efficiency of an internal combustion engine is between 35% and 45%, and that of an electric motor is between 85% and 95% (Salas *et al.*, 2013).

Fig. 3. Evaluated electric motor boat.

The reason to include this electric motor boat in the study was to answer the question whether they are also more friendly with the environment, contrasted with those powered by internal combustion motors, when emitted underwater noise is considered.

4.3. Measurement procedures

Measurements of underwater emitted noise are carried out while the boat under evaluation passes in front of the hydrophone at a defined distance. Measurements were made for three boat velocities. For the internal combustion engine boats, velocities were 1000, 3000, and 6000 rpm. For the electric motor boat, velocities were 1100, 3000, and 5500 rpm.

Figure 4 shows the area of the Valdivia River where evaluations are carried out. Figure 5 shows the boat track during measurement and the hydrophone position. This is shown only as a reference, since position and relative distance changed between measurements because the hydrophone is allowed to drift during the

Fig. 4. Area of Valdivia River where the study was made.

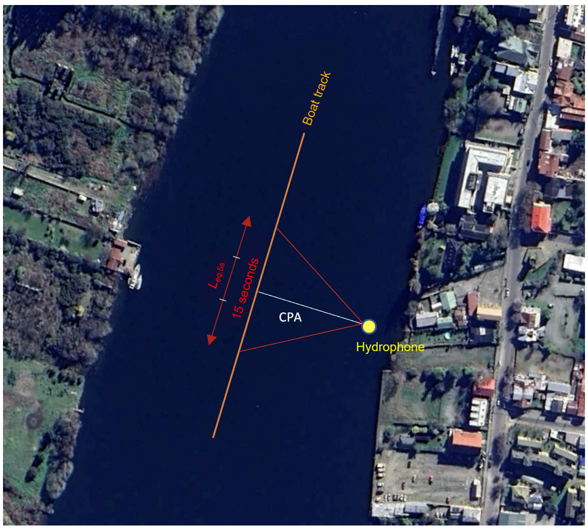

Fig. 5. The orange line shows the boat track in front of the hydrophone and the yellow circle indicates the hydrophone position.

measurements, thus avoiding hydrodynamic noise of low frequency that may be produced by currents or tides if the microphone is stationary. Measurements were made during high tide, with atmospheric conditions without rain or wind and Beaufort wind force scale between 0 and 1 (Hydrographic and Oceanographic Service of the Chilean Navy, 2002). The river depth is from 8 to 10 meters in the area where measurements were made.

The hydrophone and its floating buoy are displayed from the kayak over which the recorder and the operator stay. The hydrophone is submerged as deep as 4 meters. Through a communication radio, instructions are given to the vessel to start the measurement. The distance at which the boat passes in front of the hydrophone is measured through an optical rangefinder. The boat follows a track of approximately 250 m long in front of the hydrophone (see Fig. 5). The 4 meters correspond to half of the depth to which the marine bottom is located. The underwater sound pressure depends on the depth due to the Lloyd's Mirror effect (Carey, 2009). For a depth of 4 m this effect affects frequencies lower than 93 Hz (Urick, 1996; National Physical Laboratory, 2014). However, this is a comparative study, where all sound emissions evaluated will be affected by this effect.

From the audio file recorded during the passage of the boat, a time interval of 15 seconds centered on the time where the boat reached the shortest distance to the hydrophone is selected. This distance is called closest point of approach or CPA, and corresponds to the distance measured with the optical rangefinder (see Fig. 5) (ISO 17208, 2012; ANSI S12.64, 2009). In this work, the time where the CPA occurs is determined through the interference pattern produced due to the sound reflection over the marine bottom (see Fig. 6) (Bjørnø, 2017; Carey, 2009). From this audio file, three equivalent noise levels $L_{eq,T}$ of 5 seconds are obtained (see Eq. (1)). Central $L_{eq,5\text{s}}$ is chosen as the underwater noise emitted by the boat during its passage in front of the hydrophone (see Figs. 5 and 6). Thus, this level will represent the worst condition on the receiver, since it only considers the highest emission interval. This method differs from what is indicated for standardized methods, where an rms level is measured for a time interval called data window period or DWP (ISO 17208, 2012, ANSI S12.64, 2009).

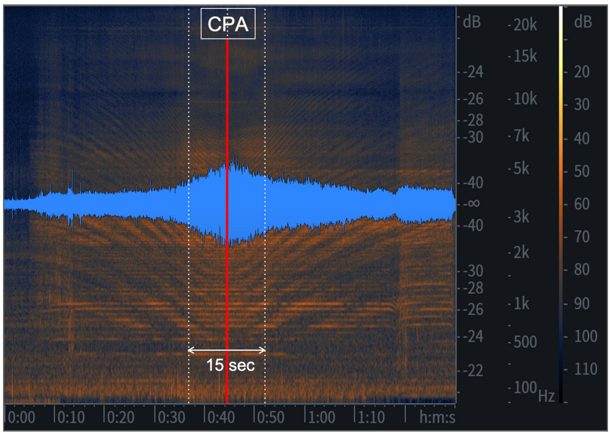

Fig. 6. Waveform and spectrogram. Example of a 15-second time interval centered on the point of the shortest distance from the boat to the hydrophone or CPA.

The descriptor equivalent noise level $L_{eq,T}$ of a fluctuating noise of the time interval T gives the continuous noise level possessing the same amount of energy as that of the fluctuating noise, in the same time interval T. The formula for $L_{eq,T}$ is:

$$L_{eq,T} = 10\log\left[\frac{1}{T}\int_0^T \left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\right] \text{ [dB]}, \tag{1}$$

where $p(t)$ is the instant sound pressure in the considered time interval T, and p_0 is the reference pressure equal to 1 μPa. Likewise, noise level may be expressed as an RMS value through the expression:

$$L_p = 20\log\left(\frac{p_{\text{RMS}}}{p_0}\right) \text{ [dB]}, \tag{2}$$

with

$$p_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T (p(t))^2} \text{ [dB]}, \tag{3}$$

where Eq. (2) gives the same value as that given by Eq. (1) for an equal time T.

Another noise descriptor used in underwater acoustics is the sound exposure level SEL. The formula for SEL is:

$$\text{SEL} = 10\log\left(\int_0^T \left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\right) \text{ [dB]}. \tag{4}$$

The SEL descriptor gives the total energy contained in the sound, where the energy of a sound is proportional to the time integral of the pressure squared. The descriptors L_{eq} and SEL are related through the following equation:

$$\text{SEL} = L_{eq,T} - 10\log\left(\frac{1}{T}\right) \text{ [dB]}, \tag{5}$$

equation that considers the time interval T with which the L_{eq} level was obtained.

Similarly, if one has a sound with a constant amplitude level L_p over time, one can obtain the total energy level for an exposure time of duration t in seconds, through the equation:

$$\text{SEL} = L_p + 10\log(t) \text{ [dB]}. \tag{6}$$

4.4. Correction by distance and source level

To obtain the source levels $L_{p,1\text{m}}$ of the evaluated boats, which is the noise level emitted by the source at a distance of 1 m, noise levels obtained during measurements must be corrected based on the distance they were made. There are different theoretical models for the propagation of underwater noise, where spherical propagation is assumed for large depths and cylindrical propagation is assumed in the presence of sound channels or certain conditions of shallow waters (Richardson *et al.*, 1995). In shallow waters, the type of marine bottom may widely change the loss of sound propagation, where for example, if the bottom is too absorbent, even a behavior closer to spherical may be found (Richardson *et al.*, 1995).

There are many environmental factors that influence the transmission of sound in shallow water, so developing adequate theoretical models is very complicated. Theory and empirical data are commonly combined to obtain reliable propagation predictions. In very shallow water, with sound wavelengths λ comparable to water depths, sound propagation can be analyzed using the mode theory. This theory indicates that if the effective depth of the water is less than $\lambda/4$, the wave will experience very large propagation losses. To accommodate the large variability observed in sound propagation in shallow water, semi-empirical propagation models have been designed for shallow water applications (Richardson *et al.*, 1995).

The place of the river where this study was carried out presents a depth between 8 and 10 meters, with a mud bottom. According to the mode theory, this location has a low cut-off frequency for the sound propagation equal to 46 Hz. However, for cases of shallow water, it is common to use semi-empirical models of sound propagation. In field studies with comparative purposes, as is the case in this study, it is usual to use a sound propagation between spherical and cylindrical, as the attenuation shown by Eq. (7) (National Oceanic and Atmospheric Administration, 2020; California Department of Transportation, 2020; McGarry *et al.*, 2020; Servicio de Evaluación Ambiental, 2022). This is a recommended practical model, since it provides a pragmatic estimation of transmission losses (National Physical Laboratory, 2014; Marine Management Organisation, 2015). Due to the above, this model was used to obtain the source level in this work:

$$L_{p,1\text{m}} = L_{eq,T} - 15\log\left(\frac{1}{d}\right) \quad [\text{dB}], \tag{7}$$

where $L_{p,1\text{m}}$ is the source level and d is the distance to the source from where $L_{eq,T}$ was measured (CPA distance). The sound propagation model used in this study is correctly adjusted to the empirical results (see Figs. 7–10). The period time T used in this work was 5 seconds.

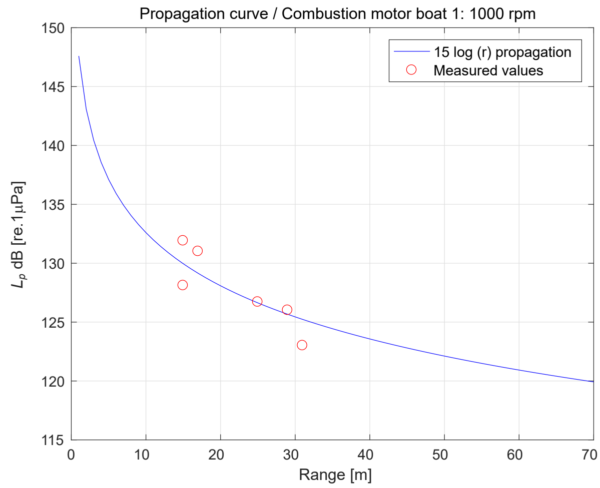

Fig. 7. Comparison between calculated transmission loss, distance and those levels obtained during measurement for the combustion boat 1, at velocity 1000 rpm.

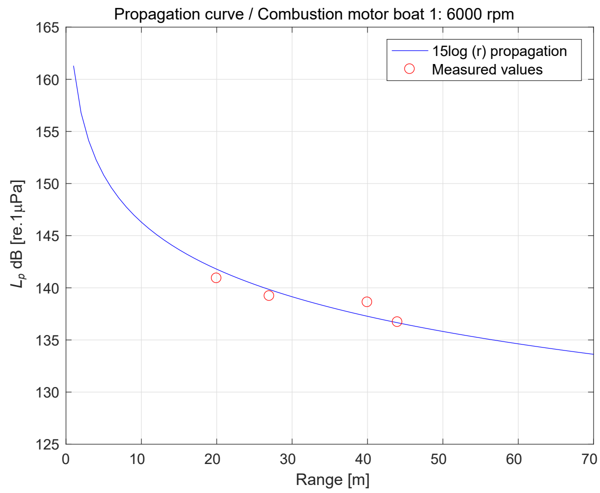

Fig. 8. Comparison between calculated transmission loss, distance and those levels obtained during the measurement for combustion boat 1, at velocity 6000 rpm.

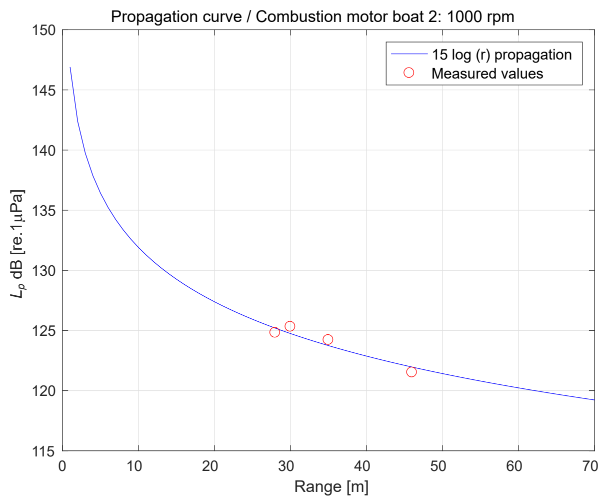

Fig. 9. Comparison between calculated transmission loss, distance and those levels obtained during the measurement for combustion boat 2, at velocity 1000 rpm.

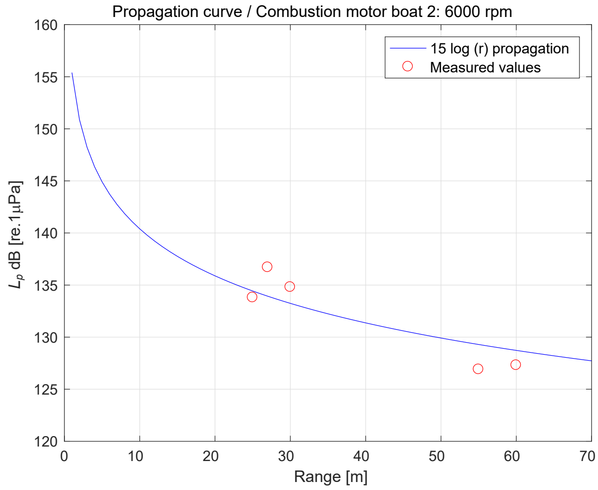

Fig. 10. Comparison between calculated transmission loss, distance and those levels obtained during the measurement for combustion boat 2, at velocity 6000 rpm.

In shallow waters and estuaries, where continuous tide changes occur, a dependence between sound velocity and depth is little probable, since a column of mixed and isothermal water is produced (Marine Management Organisation, 2015). Sound absorption was not considered in this study, since it is negligible for distances under 100 m (Richardson *et al.*, 1995; Urick 1996; Marine Management Organisation, 2015).

5. Results

5.1. Source levels

For the three boats evaluated in this study, 44 measurements were made, with a minimum of 13 measurements per boat. Measurements with three different velocities were carried out for each boat: highest, mid and lowest velocities, which corresponded to 6000, 3000, and 1000 rpm, respectively, for internal combustion motor boats; and to 1100, 3000, and 5500 rpm, respectively, for the electric motor boat. A minimal of 4 measurements were carried out for each one of these velocities.

Measurements took place between September 2018 and January 2020, always under weather conditions of no rain or wind and a Beaufort wind scale between 0 and 1 (Hydrographic and Oceanographic Service od the Chilean Navy, 2002). This allowed working with very low levels of natural background noise, with values between 99 dB and 101 dB [re.1µPa]. The hydrophone depth was constant at 4 meter. The distance between the hydrophone and boats (distance d) constantly varied due to the field conditions under which the study was carried out.

A 15-second time interval centered on the closest point between the boat and the hydrophone (CPA), was selected from audio files. Three levels $L_{eq,T}$ of 5 seconds were taken from this range. Central $L_{eq,5s}$ showed the highest level and was chosen in this work as the level emitted from the ship. Thus, by using this emission level, the worst condition is being considered when evaluating environmental impact. Tables 2–4 show levels $L_{eq,5s}$ obtained and those distances they were measured at.

Table 2. Sound pressure levels measured for the electric motor boat; d is the measurement distance.

No.	Electric motor boat $L_{eq,5s}$ dB [re.1µPa], d [m]					
	1100 rpm		3000 rpm		5500 rpm	
	$L_{eq,5s}$	d	$L_{eq,5s}$	d	$L_{eq,5s}$	d
1	106.4	7	113	7	123.5	7
2	110.9	7	113.9	7	125.9	7
3	110.8	7	112.8	7	122.9	7
4	111.4	7	114.6	7	122.1	7
5	111.5	7	115.1	7	122.4	7
6					121.5	7
7					122.7	7

Table 3. Sound pressure levels measured for the combustion engine boat 1; d is the measurement distance.

No.	Combustion motor boat 1 $L_{eq,5s}$ dB [re.1µPa], d [m]					
	1000 rpm		3000 rpm		6000 rpm	
	$L_{eq,5s}$	d	$L_{eq,5s}$	d	$L_{eq,5s}$	d
1	123	31	131.6	19	140.9	20
2	128.1	15	127.7	35	138.6	40
3	131	17	133.2	20	139.2	27
4	126	29	129.4	35	136.7	44
5	131.9	15				
6	126.7	25				

Table 4. Sound pressure levels measured for the combustion engine boat 2; d is the measurement distance.

No.	Combustion motor boat 2 $L_{eq,5s}$ dB [re.1µPa], d [m]					
	1000 rpm		3000 rpm		6000 rpm	
	$L_{eq,5s}$	d	$L_{eq,5s}$	d	$L_{eq,5s}$	d
1	121.5	46	123.6	40	126.9	55
2	124.2	35	124.8	41	133.8	25
3	125.3	30	125.3	42	134.8	30
4	124.8	28	128.4	27	136.7	27
5					127.3	60

To obtain the source levels $L_{p,1m}$ Eq. (7) was used. This transmission loss by distance was the one that best fitted those field values obtained. This fitting may be appreciated in Figs. 7–10, which show some of the obtained results.

Source levels obtained for the assessed boats, estimated from values presented in Tables 2–4, and Eq. (7) are shown in Figs. 11–13.

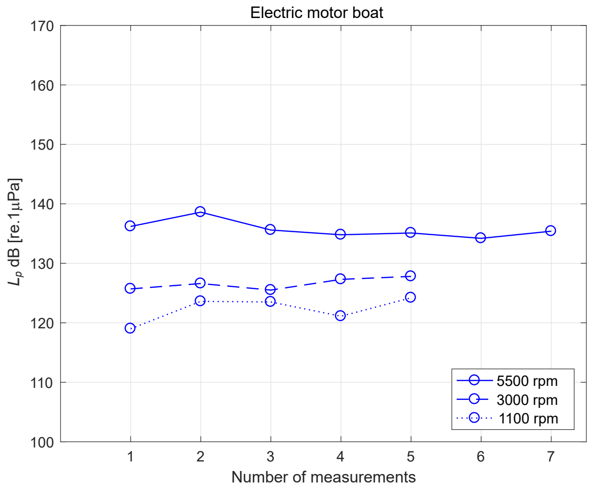

Fig. 11. Source levels $L_{p,1\text{m}}$, obtained for the electric motor boat.

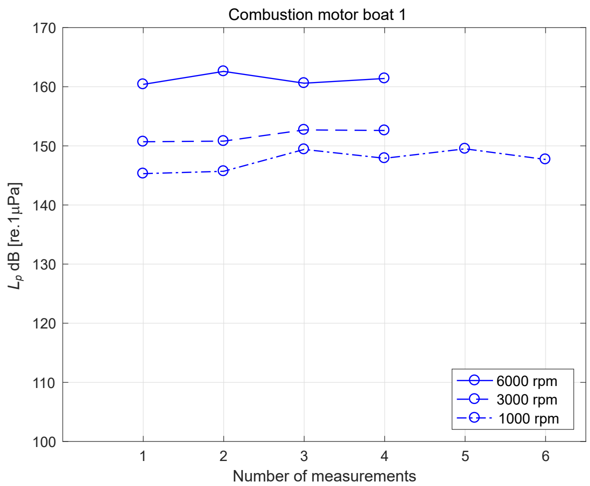

Fig. 12. Source levels $L_{p,1\text{m}}$, obtained for the combustion motor boat 1.

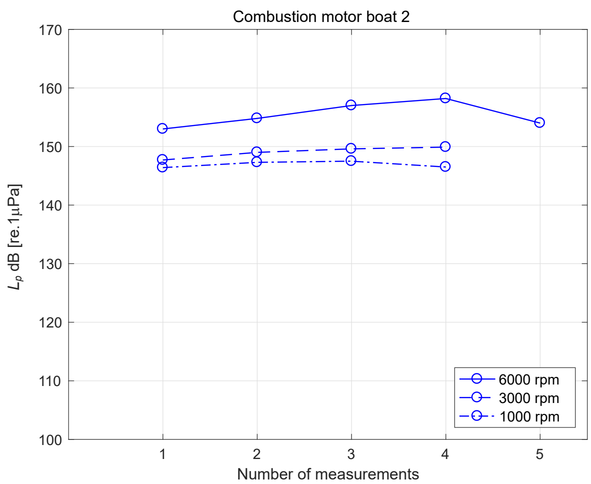

Fig. 13. Source levels $L_{p,1\text{m}}$, obtained for the combustion motor boat 2.

Now, the average source levels, together with their standard deviation s, uncertainty and highest and lowest levels are shown in Table 5 and Figs. 14–16. The uncertainty of the measurements was estimated through a confidence interval CI, calculated with a confidence level of 95% and using t-Student's criterion (Velasco Luna, 2002).

Table 5. Average values of the measured source levels $L_{p,1\text{m}}$ of the evaluated boats, together with their standard deviation s, confidence interval CI and lowest and highest values.

Electric motor boat, L_p dB [re.1µPa]					
Velocity	$L_{p,1\text{m}}$	s	CI	$L_{p,\max}$	$L_{p,\min}$
1100 rpm	122.3	2.17	122.3 ± 3	124.2	119
3000 rpm	126.6	0.99	126.6 ± 1	127.8	125.5
5500 rpm	135.7	1.43	135.7 ± 1	138.6	134.2
Combustion motor boat 1, L_p dB [re.1µPa]					
Velocity	$L_{p,1\text{m}}$	s	CI	$L_{p,\max}$	$L_{p,\min}$
1000 rpm	147.6	1.8	147.6 ± 2	149.5	145.3
3000 rpm	151.7	1.07	151.7 ± 2	152.7	150.7
6000 rpm	161.3	1	161.3 ± 2	162.6	160.4
Combustion motor boat 2, L_p dB [re.1µPa]					
Velocity	$L_{p,1\text{m}}$	s	CI	$L_{p,\max}$	$L_{p,\min}$
1000 rpm	146.9	0.56	146.9 ± 1	147.5	146.4
3000 rpm	149	0.99	149 ± 2	149.9	147.7
6000 rpm	155.4	2.15	155.4 ± 3	158.2	153

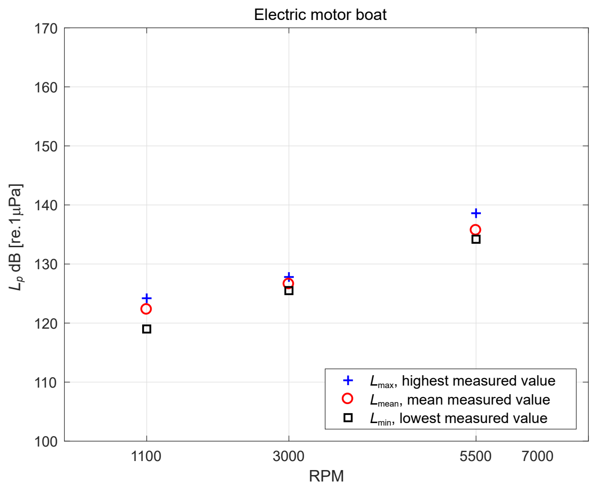

Fig. 14. Average source levels $L_{p,1\text{m}}$ of the electric motor boat, together with highest and lowest levels for the three evaluated velocities.

5.2. Noise emission spectra

The 1/3 octave band noise spectra for the three assessed boats were obtained, which are shown in Figs. 17, 18, and 19. Spectra are from the sound emissions corresponding to the moment when boats pass in front of the hydrophone and at the closest distance or

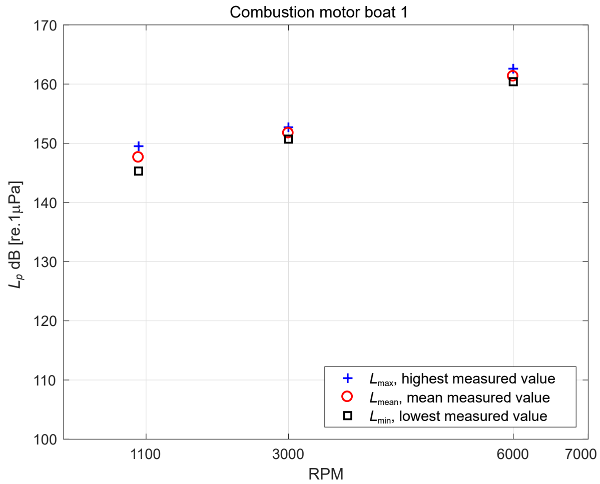

Fig. 15. Average source levels $L_{p,1\mathrm{m}}$ of the combustion motor boat 1, together with the highest and lowest levels, for the three evaluated velocities.

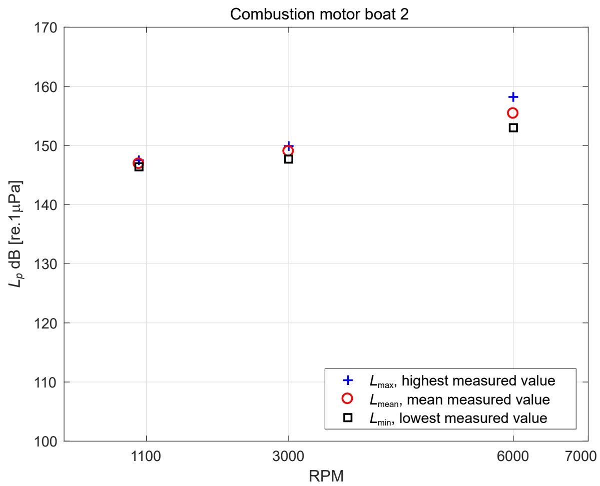

Fig. 16. Average source levels $L_{p,1\mathrm{m}}$ of the combustion motor boat 2, together with the highest and lowest levels, for the three evaluated velocities.

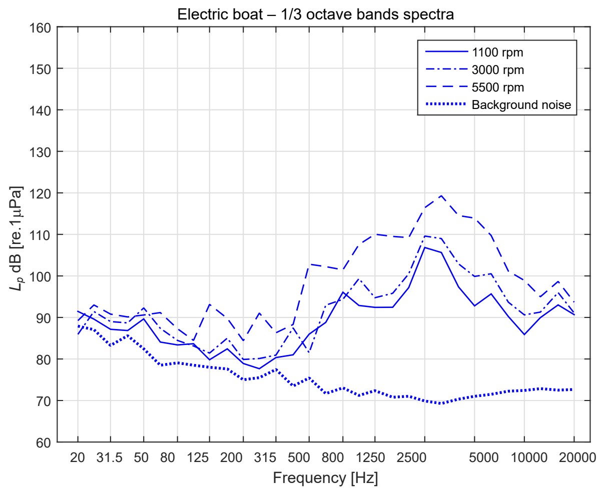

Fig. 17. 1/3 octave bands spectra of the electric motor boat, for the three velocities evaluated. Likewise, the background noise registered in the area is shown.

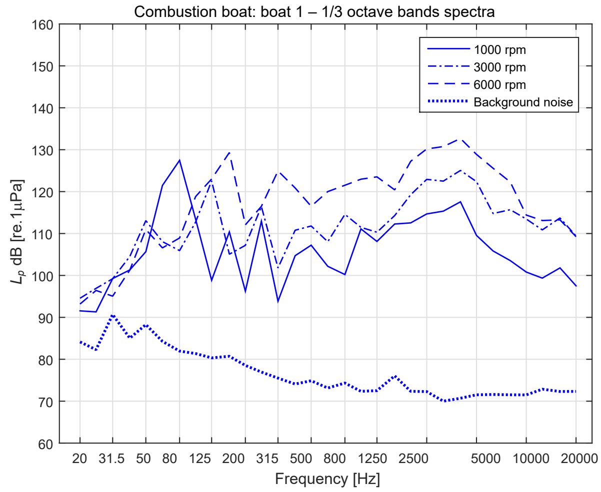

Fig. 18. 1/3 octave bands spectra combustion motor boat 1, for the three velocities evaluated. Background noise measured in the area is also shown.

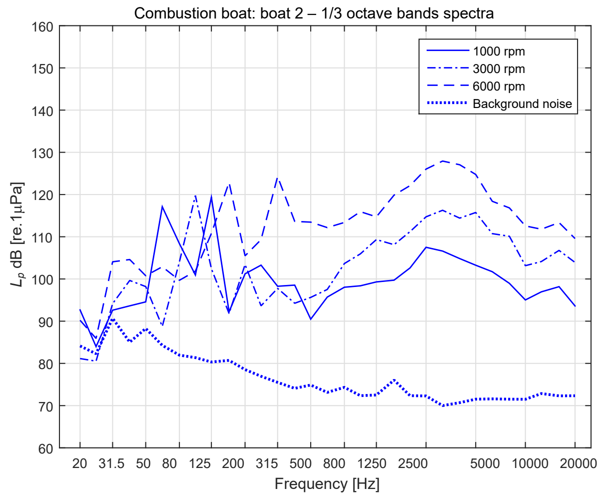

Fig. 19. 1/3 octave bands spectra of the combustion motor boat 2, for the three velocities velocities evaluated. Background noise measured in the place is also shown.

CPA. Spectra correspond to only one passage of the boat in front of the hydrophone and for each one of the three velocities. Together with the boats spectra, figures show the spectra of the background noise evaluated in the area.

6. Discussion

This work comprises a comparative study of the underwater noise levels emitted by boats with similar dimensions and passenger's capacity, used in identical touristic duties, though using different propelling systems. Results show that source levels $L_{p,1\mathrm{m}}$ of the assessed boats propelled by internal combustion outboard motor are between 145.3 dB and 162.6 dB [re.1µPa], for the combustion motor boat 1, and between 146.4 dB and 158.2 dB [re.1µPa], for the combustion motor boat 2. Source levels $L_{p,1m}$ obtained for the electric motor boat fluctuated between 119 dB and 138.6 dB [re.1µPa]. All these emission levels were registered for the boats velocities between 1000 rpm and 6000 rpm.

The background noise level with which measurements were carried out was between 99 dB and 101 dB [re.1µPa]. Wide band levels measured and observed, emitted by the evaluated sources, were always superior to the background noise observed over 10 dB, even for the lowest velocities. Regarding the lowest 1/3 octave frequency bands due to differences inferior to 10 dB, some level corrections were made. Nevertheless, these corrections did not influence the broadband level obtained.

Source levels $L_{p,\mathrm{1m}}$ obtained in this work, corresponding to boats propelled by internal combustion engines, coincide with those levels shown by other studies for the same type of boats (Richardson *et al.*, 1995; Marine Management Organisation, 2015; Erbe, 2002; Wladichuk *et al.*, 2019). Regarding levels emitted by the electric motor vessel, it was not possible to find literature showing values of emission levels for this type of boat.

According to the results obtained, the boat propelled by electric motor emits underwater noise levels much lower than those emitted by the internal combustion boats. For the low velocity (1000–1100 rpm), the underwater noise level emitted by the electric motor boat is approximately 25 dB lower than the level emitted by the combustion motor boat 1, and 24.6 dB lower than the level emitted by the combustion motor boat 2. For the mid velocity (3000 rpm), the electric motor boat emits approximately 25.1 dB less than the level emitted by the combustion motor boat 1, and 22.4 dB less than the emissions of the combustion motor boat 2. For the highest velocity (5500–6000 rpm), the level of underwater noise emitted by the electric motor boat is approximately 25.6 dB lower than the level emitted by the combustion motor boat 1, and 19.7 dB lower than the level emitted by the combustion motor boat 2.

This difference between underwater noise levels emitted by the electric motor boat and those levels emitted by combustion motor engines arises as highly important when we consider their use inside marine protected areas, in duties such as marine mammal watching and also regarding the fulfillment of the highest recommended noise levels to avoid any type of disturbance, temporal damage TTS or permanent damage PTS, to the observed species (NMFS, 2016; 2018). Letting the source level $L_{p,\mathrm{1m}}$ in Eq. (7) be the dependent variable, one can see that a difference of 25 dB between the level of underwater noise emitted by two boats means that there will be an approximate difference of 46 times in the closest distance that the less noisy boat could reach when approaching a certain marine mammal, compared to the closest distance that the loudest boat could reach, to generate the same level of noise on the animal exposed to noise.

Similarly, Eq. (6) shows that this 25 dB difference means a 316 times lower accumulated energy for an exposure to noise emitted by the electric boat compared to the exposure to noise emitted by the boat with an internal combustion engine.

The 1/3 octave band frequency spectra agree with the obtained source levels $L_{p,\mathrm{1m}}$. It can be clearly seen how the level of frequency components increases as velocity of boats increases. Combustion engine boats present similar spectra regarding shape and behavior (see Figs. 18 and 19). In them, low-frequency tonal components are observed, which are produced by the mechanical vibrations of the rotating parts of the motor. The frequency of the tonal components increases with increasing propeller rpm. A continuous spectrum is observed over 500 Hz, which is mainly due to the cavitation noise produced by the propeller, which is of impulsive origin and broadband. Spectra show how the amplitude relation between tonal components and continuous components goes changing. Thus, as the boat velocity increases, cavitation noise produced by the propeller becomes dominant in noise emissions over the mechanical noise produced by the motor, which is predominant at low velocities.

Regarding the emission spectra of the electric motor boat (see Fig. 17), the cavitation noise produced by the propeller increases as the boat velocity increases. The cavitation noise produced by this vessel is lower than that produced by combustion motor boats for all evaluated velocities. What is interesting in these spectra is that low frequency tonal components, corresponding to periodic vibrations of the motor and propeller, show extremely low amplitudes. This may be due to different reasons. As it is an electric engine, the high periodic vibration produced by combustion does not exist; the rotating parts of the motor – as it is an inboard motor – are inside the hull; and finally, the modern design of the hull allows for a less turbulent water flow around the propeller, which reduces the excitation of resonances in the propeller (Urick, 1996).

7. Conclusion

The results reached in this study show that for the type of evaluated vessels, using electric motor boats instead of those commonly used boats – propelled by internal combustion motors – underwater noise levels emitted by an amount between 20 dB and 25 dB are reduced. This reduction in the level of emitted noise allows the electric boat, when necessary, a closer approach to the animal under observation. Furthermore, it will allow larger time of observation or a much lower accumulated exposition of the animal to the noise.

A comparative study to evaluate the acoustic impact that each one of these vessels would cause over a determined species would be very interesting and necessary.

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