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DEVELOPMENT OF THE AUTONOMOUS UNDERWATER NOISE RECORDER

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Summary. An underwater noise is the most pervasive type of physical energy that spreads in underwater marine environment. The concerns regarding man-made underwater noise effects on the aquatic animals became prominent within scientific communities. The determination of underwater noise levels became very actual either for environmental monitoring or scientific research purposes. Various tools for acquisition of the underwater sound as well, modelling became available, although some techniques are costly and requires special considerations. One of the examples are the sound recording devices containing hydrophones along with digital sound acquisition systems used for recording of ambient (continuous) underwater sounds. By the date there are already developed the international and European standards for monitoring the long term (yearly) underwater continuous noise levels. However, the techniques known to be able to record the short and mid-term noise levels can serve for the research purposes greatly. In this research the cost efficient autonomous underwater sound recorder was developed, with the purpose to record an ambient underwater noise continuously and autonomously for the periods of up to 15 days, following the already known methods. In this paper we present the steps of the development of the autonomous recorder, its features and capabilities as well, calibration results of the underwater sound recording system.

Keywords: Environmental pollution, underwater noise, hydrophone, digital audio recorder.

Introduction

There are many kinds of anthropogenic energy that human activities introduce into the marine environment including sound, light and electromagnetic, heat as well, radioactive energy. Among these, the most widespread and pervasive kind of energy is underwater sound (van der Graaf et al., 2012). The global shipping trends inevitably are increasing, where the number and size of commercial vessels in the world’s merchant fleet have increased during the last 50 years significantly (Hildebrand, 2009). This increase in global shipping trends has raised the concern that resulting radiated underwater noise energy is causing widespread behavioural and physiological effects on marine animals (Merchant et al., 2019). Due to these concerns the anthropogenic underwater noise measurements became actual in the light of environmental protection and wildlife conservation.

The history of the measurements of underwater sound dates back to the World War II. At that time the calibrated hydrophones were not available. Between 1940 and 1950’s the barium nitrate piezoelectric ceramics started to be used in hydrophone applications. The availability of hydrophones capable of operating in Oceanic environments along with primitive data acquisition systems allowed implementing the underwater sound research. The later developments of lead zirconate titanate enabled the development of the wide frequency band hydrophones that are used widely to investigate underwater sounds (Carey & Evans, 2011).

Underwater sound measurements can be implemented in a few ways – using the fixed hydrophones or moving hydrophones, i.e. by attaching them to a towed cable or to marine animals. The fixed location measurements can be compared against the criteria for environmental sound (van der Graaf et al., 2012). By the date there are variety of the autonomous acoustic recording systems capable to store an acoustic data to the hard drives or memory cards at the periods extending up to 12 months, where these loggers can be either popping up to the water surface or to be bottom resting (Au & Hastings, 2008). The price of this kind of recorders starts from ~5500 $ (Ocean Instruments NZ, 2020), where the cost of the measurements can increase significantly if the loss of equipment occurs, i.e. entangled equipment in the trawling nets as well, due to the vandalism and negligent equipment destruction. The techniques known to be able to record the short and mid-term noise levels can serve for the research purposes as well, especially in the shallow water areas and can be developed for affordable price.

In this paper the methods for the development of the cost efficient autonomous underwater sound er, capable to record the underwater sounds continuously for the period of up to 15 days is presented. Along the calibration data, acquired during its development process is presented, that resulted with frequency response of the autonomous recorder having flat response in the frequency range between 0.1–1 kHz. In this frequency range the systems response showed the deviation of the SPL's from the SPL's of the reference sound level meter reaching the value of 4 dB.

Methods and materials

The autonomous underwater sound recorder was developed following the already known techniques (see Cetacean Research Technology, 2020 as well; Au & Hastings, 2008).

The frame for the autonomous recorder platform (the rig) was welded from the square steel hollow piles, having the diameter of the 25×25 mm (wall thickness 2 mm), with the resulting frame size of 600×600×600 mm and the 20 kg additional round weight ballast, welded to the bottom of the rig.

The plastic transparent enclosure was screwed to the frame. The enclosure consists of the two parts: the tube (diameter of 150 mm, length of 350 mm) with the thread and the O-ring and the plastic endcap, having two side cavities for external connections. The hydrophone was screwed in to the side cavity of the endcap. The internal side of the endcap was covered with the ~20 mm layer of the industrial resin to avoid unnecessary water leakages trough the cavities. The operating pressure of the enclosure is up to the 8 bars (depth in the seawater up to 79.7 meters).

The Aquarian Audio® hydrophone H2c mounted on the acoustic recorder (hydrophone dimensions 25×58 mm) has the horizontal omnidirectional response, the sensitivity of the –180 dB re.1V/μPa, +/–4 dB in 20 Hz–4 kHz frequency range. The hydrophone has the useful frequency response in 10 Hz–100 kHz range (approximate sensitivity at 100 kHz, –220 dB re.1V/μPa).

Output impedance of the hydrophone is 2 kΩ and operating depth up to 80 meters. The polychloroprene insulated (XLR) connector was welded to the hydrophone wire. The H2c hydrophone requires bias power from the device with which it is used (Aquarian Audio & Scientific, 2020).

The professional four cannel digital audio recorder TEAC TASCAM DR-40X® was placed in the enclosure. Digital audio recorder has the frequency response in 20 Hz – 40 kHz (+0/–1 dB) frequency range, depending on the sampling frequency, the sampling frequencies can be set as 44.1 kHz / 48 kHz or 96 kHz and adjustable bit depth 16 or 24. It has a professional nominal line input of +4 dBu (peak amplitude 1.736 Volts), line input impedance of 10 kΩ. The signal to noise ratio of the recorder is >94 dB; the information of the dynamic range is not available for DR-40x, although its recent predecessor DR-40 holds the 63 dB dynamic range (see Avisoft Bioacoustics, 2020). The recorder supports the 48 Volt Phantom power with devices that requires the Bias power.

The battery pack to power the recording system was constructed. The battery pack contains 6 battery holders for D/RL20 batteries, in total for 12 D type batteries. The battery pack was connected to power the system with 6 Volts power through the micro-B USB connector. The electric rectifier filter power board with power indicator was mounted on the battery pack to equalize power supply with USB power standard.

The schematics of the electronics along with its components of the developed underwater sound recorder are given in the Figure 1.

The output of the recording system is the waveform audio file format (WAV) files, having the digital data normalized to the +/–1 amplitude range. The knowledge of the voltage range of the analogue to digital converter (ADC) is necessary to readout the voltage amplitude signal (for developed acoustic rig +4 dBu).

The amplitude voltage signal produced by the system was read out from the recorder's memory card in MATLAB® software and defined by the equation (Merchant, 2014):

$$X_V = \frac{V_{Peak} X_{bits}}{2^{N-1}} = V_{Peak} x_{Wav}, \quad (1)$$

where: V_{peak} is the zero-to-peak voltage range of the ADC; $X_{bits} = 2^{N-1} X_{WAV,}$ with N being the bit resolution (16 or 24).

The sound pressure levels (SPL's) of the given test signals were acquired using the recording chain of the developed rig (signals acquired using the 44.1 kHz sampling frequency and 16-bit resolution) as well, processing the signals with the Virtual Sound Level Meter v0.42 in

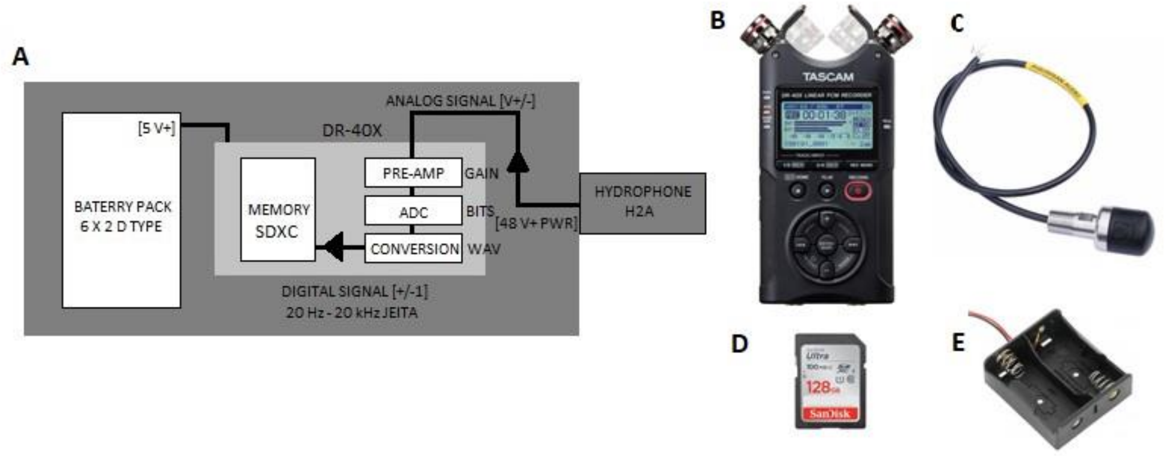

Figure 1. The schematics of the electronics along with its components of the developed underwater sound recorder: a – schematic representation of the electronics of the developed underwater sound recorder; inner parts: b – professional audio digital recorder; c – low noise hydrophone; d – Secure Digital eXtended Capacity (SDHC) memory card; e – battery pack cell

MATLAB® application, adding the 61.5 dB value of the air and water medium reference difference (20 µPa to 1 µPa) and sound pressure difference in air and water medium (Au & Hastings, 2008) to the values in dBA.

The SPL's were defined as unweighted sound pressure levels that are given by (de Jong et al., 2011):

$$SPL = 10Log_{10} \frac{1}{T} \int_0^T \frac{P(t)^2}{P_{ref}^2} dt, \qquad (2)$$

where: SPL is the sound pressure, units dB re.1µPa^2; $P(t)$ instantaneous sound pressure; P_{ref} reference sound pressure (1 µPa) and T – integration time (1 second), with no windowing of the signal.

The sound power spectral density levels (PSD) were acquired using the PSD mode in Virtual Sound Level Meter, that computes the Welch Modified periodogram while finding discrete-time Fourier transform (DFT) of the samples. The periodograms are averaged at each frequency to get the estimated PSD spectrum for the entire measurement file (Muehleisen & McQuillan, 2011). The processing setting was used – the FFT size of the 4096 points, using *Hanning* window, 50% window overlap. The PSD assumed as the sound power spectral density of squared sound pressure per unit of the frequency bandwidth *Q(f)* to the reference sound pressure, expressed as the equation (de Jong et al., 2011):

$$PSD = 10Log_{10} \left(\frac{Q(f)}{P_{ref}^2 / f_{ref}} \right), \qquad (3)$$

where: *Q(f)* – contribution of the P^2 per unit of the frequency bandwidth; P_{ref} – reference sound pressure (1 µPa), reference frequency 1 Hz (T = 1s), units dB re.1µPa^2/Hz.

The sensitivity of the recording chain was tested at low frequencies where the sensitivity *Mv* is the ratio of its output voltage to the sound pressure in the medium surrounding it, using an equation:

$$M_v = \frac{V_h}{P_h}, \qquad (4)$$

where: V_h is the read out of the voltage and P_h is the pressure in µPa (National Physical Laboratory, 2018; Biber et al., 2018).

The frequency response of the recording chain was tested at the premises of the Marine Research Institute of the Klaipėda University, using the Multi-Function Environment Meter (Sound Level Meter) Model-8820, with electric condenser microphone, having the frequency range of 30 Hz–10 kHz, accuracy of ±3.5 dB at 94 dBA sound level of 1 kHz sine wave, provided by the Waterborne Transport and Air Pollution Laboratory of the Klaipėda University, that was used as the reference microphone. The sound tones (square wave signals at different frequencies) were generated using the interactive Online Tone Generator (Szynalski, 2020), as well, using the laptop computer with connected speakers.

The self-noise of the recording chain was tested, retrieving the part of the data, having the white (silent) noise. These white noise sound levels were compared to the Sea wind force Zero state noise spectrum.

In the absence of sounds from ships as well, marine life, underwater ambient sound levels depends on wind force and Sea state in the frequencies between 100 Hz and 25 kHz in marine environments. While the underwater ambient noise spectrum up to 500 Hz is often dominated by the shipping noise, the spectrum above the 500 Hz is dominated nearly always by the wind force noise and in the frequency range of 0.5–5 kHz follows the “Wenz curves” (Wenz, 1962). Isotropic Sea state of Zero noise is the noise measured under the ideal conditions of no wind, calm surface, no biological activity, and negligible shipping. It varies with the frequency and is independent of the depth and geographic location (Wagstaff, 1973). The self-noise of measurement equipment should fall bellow the Sea state of zero levels at frequencies of interest (Dekeling et al., 2013). The Sea state of Zero noise levels for this purpose were equated using the model recommended to use in the Baltic Sea by the Swedish Defence Research Agency FOI, developed by Phil et al. (2005):

$$NSL = \begin{cases} 24Log_{10}\left(1+W\right)-17Log_{10}\left(f\right)+35 \\ 20Log_{10}\left(\dfrac{f}{6}\right) \end{cases}, \qquad (5)$$

where: NSL – the spectrum noise level; f – the sound frequency in kHz; W – the wind speed in knots – its max value is the maximum between two options depending on a higher value (units dB re.1µPa^2/Hz).

Results

The developed autonomous underwater sound recording system is depicted in the Figure 2.

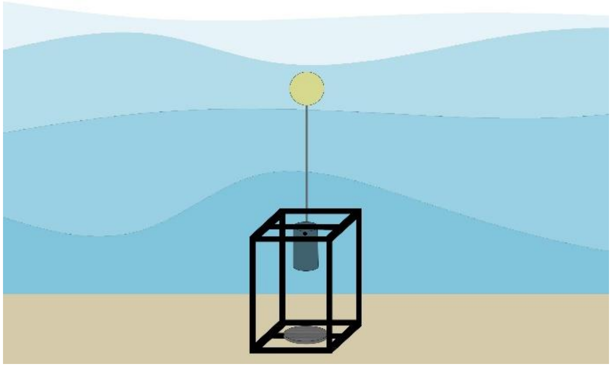

Figure 2. The developed autonomous underwater sound recording system

It was tested the frequency response of the autonomous recorder. The resulting sound pressure spectrum is depicted in the Figure 3.

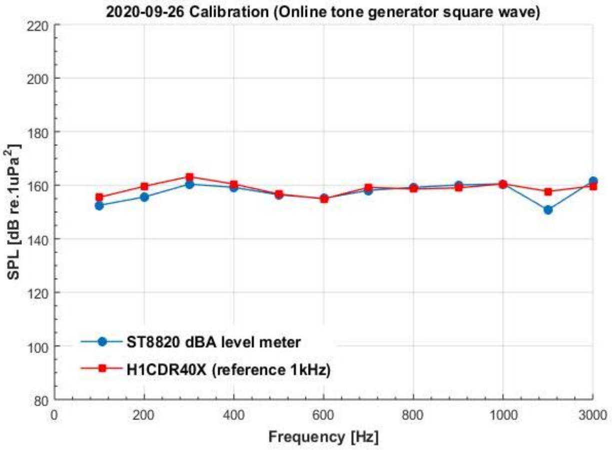

Figure 3. The frequency response to a square wave signal at different frequency bands of the recording setup

Acquired frequency response results revealed a flat response in the frequency range between 0.1–1 kHz. In this frequency range the systems response showed the deviation of the SPL’s from the SPL’s of the reference sound level meter, reaching the value of 4 dB. In the higher frequency range up to 3 kHz this deviation increased up to 7 dB and at higher frequencies this deviation was observed as even higher. The standard deviations of the developed recording system’s frequency response were obtained within the value of the 2 dB, comparing to the reference noise level meter’s standard deviations value reaching 3.4 decibel. These values of standard deviations were obtained in the frequency range of the 100 Hz–3 kHz. At higher frequencies the values of standard deviations were a bit higher although, at frequencies E. G. above 5 kHz these discrepancies has a little relevance here.

The sensitivity of the measurement chain was tested as well. The defined sensitivity of the recording rig at 1 kHz frequency band is –197.6 dB re.1V/µPa. At low frequency range the sensitivity defined as having a relatively flat response, however with deviation, reaching 4 dB in frequency range within 100–700 Hz. The sensitivity at frequencies above 700 Hz with higher deviations from average value was observed.

The voltage amplitude data was readout from the memory card of the recorder.

The Figure 4 shows the voltage amplitude recorded of the square wave signal of 1 kHz, at 44.1 kHz sampling frequency, 16-bit resolution, of the 99 dBA tone signal sound pressure level (underwater standard SPL 160.5 dB re.1µPa^2).

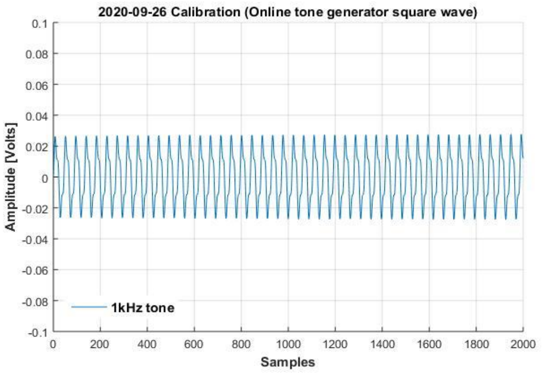

Figure 4. The voltage amplitude readout of the recording setup, extracted from the SDXC memory card of the recorder

Not all the commercially available systems would be suitable for use in the measurement of very low-level ambient noise in conditions near Sea State of Zero (Biber et al., 2018). To test the self-noise of the recording chain under consideration the results were compared against the Sea state of Zero noise levels (Eq. 5). The resulting noise levels are depicted in the Figure 5.

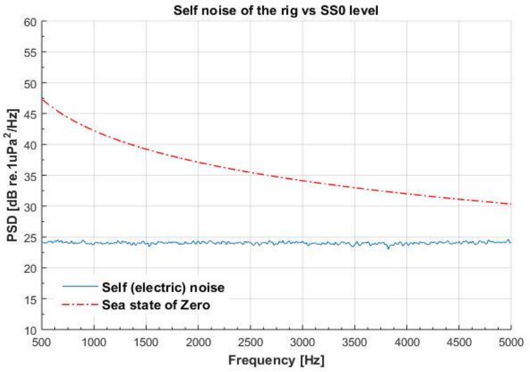

Figure 5. Sound power spectral density levels of the measured self-noise of the developed sound recording rig vs modeled Sea state of Zero level

The measured self-noise levels revealed the lower emanating white electric noise compared to the Sea state of Zero in the frequency range of 0.5–5 kHz, although at the very low frequency (bellow 50 Hz) the self-noise levels were determined as being just as Sea state of Zero levels (reference See state of "0" wind speed ~1 m/s, see Kuperman & Rough, 2007).

Conclusions and discussion

The developed autonomous sound recording system was designed to be deployed on the sea bottom at shallow areas with the depth of 79.7 meters. However, to follow the precautionary practice the deployment depth is recommended to be 50 m. The sound recording time of the system extends to approx. of 15 days, depending on the batteries (tested with Duracell D type "Long life" batteries). The tested frequency response of the recording chain revealed the flat response in the low frequency range of up to 1 kHz. At higher frequencies the deviations of sound pressure levels are increased compared to reference Sound level meter. This deviations can be attributable to the testing setting, i.e. the testing of the hydrophones and recorders are recommended to be implemented in the coupling chamber filled with water either gas or standing wave tube (Biber et al., 2018). The sensitivity of the recording chain was tested as well, that reached the –197.6 dB re.1V/μPa in 1 kHz band (compared to hydrophone sensitivity equal to –180 dB re.1V/μPa at lower frequencies). The information regarding the dynamic range of the analog-digital converter is not available yet in the literature, still used recorders recent predecessor DR-40X holds 63 dB dynamic range.

The self-noise test revealed that recording set-up is capable to record low level ambient noise slightly below Sea state of Zero (~1 m/s wind) at frequencies within 0.5–5 kHz.

Generally, the acoustic recorders to be used for underwater noise monitoring is recommended to have the sensitivity within the range of –165 to –185 dB re.1V/μPa (van der Graaf et al., 2012) and hold the flat response in the frequency range of interest. To fulfil a full calibration of the device the second features of the recorder should be known (Biber et al., 2018; Hayman et al., 2016).

1. System sensitivity;
2. System self-noise;
3. System dynamic range;
4. Directional response;
5. Frequency response.

The concluding remarks from the experimental work can be made:

- The developed autonomous underwater sound recording rig can be used for short-mid time deployments at shallow marine areas;
- The autonomous recorder has a flat frequency response in the frequency bands up to 3 kHz;
- The defined sensitivity of the recorder in 1 kHz band is –197.6 dB re.1V/μPa;
- The autonomous recorder can record the low-level ambient noise slightly below the Sea state of Zero;

- The system testing was performed in the laboratory premises, although calibration of the recording systems is recommended to be done in the coupling chamber filled with water either gas or standing wave tube, where the development of the special chamber in Lithuania should be considered;
- Finally, the equipment tests were made using the reference Sound Level Meter with condenser microphone, that has an accuracy of ± 3.5 dB, where the more accurate results can be achieved using more accurate equipment.

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AUTONOMINIO POVANDENINIO GARSO ĮRAŠYMO ĮTAISO SUKONSTRAVIMAS IR TOBULINIMAS

D. Bagočius, A. Narščius

Santrauka

Yra žinoma, kad povandeninis triukšmas – viena skvarbiausių fizinės energijos rūšių jūrinėje aplinkoje. Susirūpinimas antropogeninės kilmės povandeninio triukšmo poveikiais jūros aplinkai, t. y. vandens gyvūnijai, tapo ryškus. Tapo aktualūs povandeninio triukšmo matavimai jūrose. Šio triukšmo lygiams nustatyti sukurta nemažai metodų, kurie apima triukšmo modeliavimą ir jo matavimus. Tačiau kai kurios technologijos yra ganėtinai brangios ir reikalauja specialiųjų žinių. Vienas iš tokių pavyzdžių – povandeninio nuolatinio, t. y. foninio, aplinkos triukšmo lygių matavimai. Europos Sąjungoje yra patvirtinti ilgalaikių, t. y. metinių, povandeninio triukšmo lygių stebėsenos standartai. Tačiau technologijos, skirtos trumpalaikėms arba vidutinės trukmės triukšmo kitimo tendencijoms nustatyti (išmatuoti), taip pat gali padėti mokslo tiriamiesiems tikslams. Šiame darbe pristatomas sukonstruotas povandeninio garso įrašymo autonominis įrenginys, sukonstruotas remiantis žinomomis technologijomis ir gebantis fiksuoti povandeninį garsą (triukšmą) iki 15 parų nenutrūkstamai, taip pat aprašomi jo sukonstravimo etapai ir eksperimentiniai testavimo rezultatai.

Reikšminiai žodžiai: povandeninis triukšmas, garso įrašymas, hidrofonas, skaitmeninis įrašytuvas.