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Low-cost noise maker for testing acoustically guided unmanned vehicles

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Low-cost noise maker for testing acoustically guided unmanned vehicles

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Abstract. Testing the performance of the Acoustically Guided Unmanned Underwater Vehicle (AGUUV) prior to its deployment is essential to ensure its ability to perform the required tasks accurately. These systems can be deployed from boats or helicopters to scan areas of military and economic importance for threats. These threats such as aircrafts carriers, ships, submarines, divers, and autonomous surface vehicles. The problem of implementing a low-cost high-performance noise maker (LCNM) which is suitable for being used as a test target instead of different threats for AGUUVs is the motivation of this paper. Lab experiments and sea trials are performed using the proposed noise maker to demonstrate the proper operation of the AGUUV. Lab experiments showed that the radiated noise of the proposed noise maker has high power in the frequency band between 5 to 8 kHz. The measured signal to noise ratio (SNR) for the introduced LCNM is 30 dB in this band. The experimental results presented in this paper show the feasibility of using the proposed LCNM effectively to test the AGUUVs.

Keywords: Noise maker, unmanned underwater vehicles, target noise, acoustic target

1. Introduction

Unmanned underwater vehicles (UUV) have recently gained great importance due to their role in carrying out tasks that are sometimes difficult for humans to perform on their own. These systems have important scientific applications [1-4], and military applications [5-10].

Performance evaluation and testing the functionality of UUVs is required before deployment. Testing technique depends on the system objective. The department of homeland security and the national institute of standards and technology introduced and developed a standard test for the basic performance of marine robots [11].

In this paper we focus on testing the AGUUVs which can be used for surveillance of marine ports, and offshore oil/natural gas platforms. AGUUVs systems can search, detect, classify and track underwater threats based on their acoustic signatures. One way to test these systems is to use a low-cost acoustic target that can simulate the real threats. Noise makers (NM) are used in preparation of an acoustic target that is used in exercise or testing the AGUUV before deploying. In most cases, NM is immersed in water under a training target that has no source of sound. Fig. 1 shows a schematic drawing for a possible application of NM in testing AGUUV, and how the NM is hung under a ship that has no sources of sound while it is powered by an electrical battery or it can be hung from a helicopter to test the guidance of an AGUUV. Existing noise makers used for testing the AGUUV are outdated and no longer available or could not be easily provided according to the required specifications, and this was an incentive for us to start this study. The main purpose of this paper is to design and realize a low-cost high-performance noise maker that can simulate the acoustic signatures of possible targets of the AGUUVs.

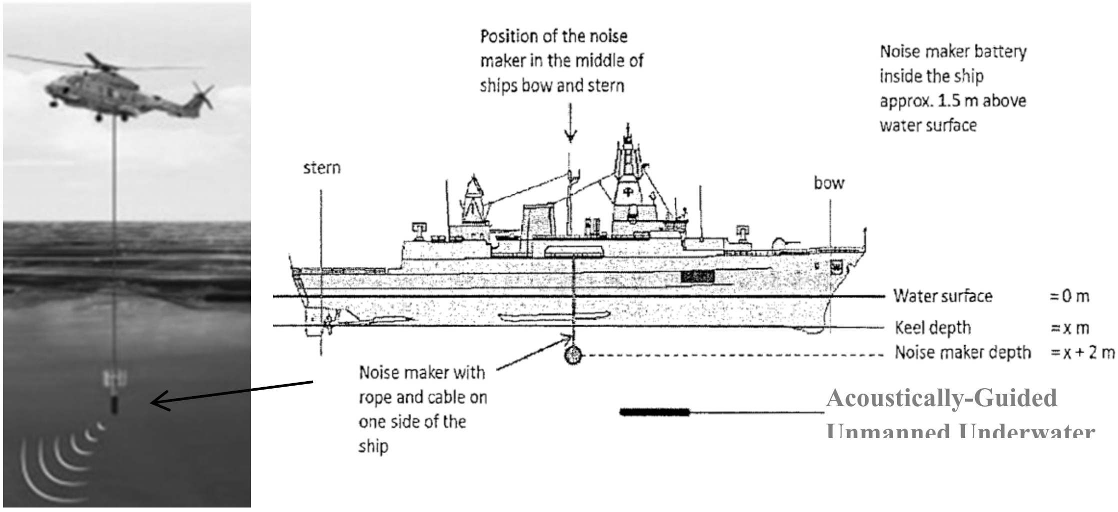

Figure 1. Application of NM in testing AGUUV.

2. AGUUV Self Noise

The investigated AGUUV uses passive sonar for detection of targets. The AGUUV has several sources of noise produced from its propeller, engine and hydrodynamic effect. A recorded acoustic signal of the AGUUV launch is analyzed to study its self-noise and reveal its spectrum characteristics. Figure 2 shows the power spectral density (PSD) of the recorded AGUUV noise measured by a standard omnidirectional hydrophone 1 meter from it (its frequency response is 0.1 Hz to 100 kHz, and sensitivity -205 dB re 1 V/µPa), fed into a data acquisition system (DAQ) (DT9857E from DATA TRANSLATION) with sampling frequency 44.1 kHz, analyzed and processed by MATLAB code. For standardization and accuracy of the results, the same measurement devices were used throughout all the experiments mentioned in the paper.

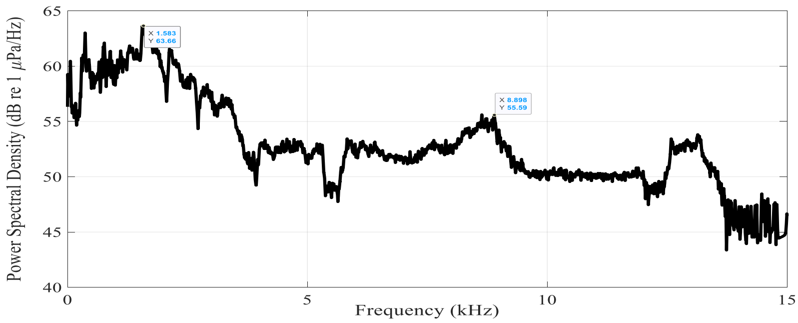

Figure 2. AGUUV Noise: PSD of the AGUUV self-noise.

Figure 2 shows that most of noise power is concentrated in frequency band <3000 Hz. It can be seen that peak power of AGUUV noise is at frequency of 1583 Hz and its level is 63.65 dB, while at higher frequency band, the self-noise of the AGUUV has a peak at 8898 Hz and its level is 55.6 dB level.

3. Radiated Noise Sources

In this section we will study acoustic noise generated by possible targets of AGUUV. The study is concentrating on spectrum rather than amplitude characteristics. Firstly, two examples of recorded noise of two surface vessels are examined. Then, two examples of some in-hand noise makers are tested. One of the tested noise makers was previously deployed as Acoustic Mine Sweeper. The second one was recently used as an acoustic target for some other type of AGUUV's. The purpose of studying the generated noise from these sources is to show the ability of the proposed low-cost noise maker to provide the same performance as the real targets and hence it can be used to effectively test the AGUUV's.

3.1 Surface Vessels Noise (SVN)

In this study, we used some sound recordings of passing ships which were obtained during current research using hydrophones to measure and record the radiated noise from different objects. The radiated noise of the first ship and the second ship shown in Figures 3 and 4 respectively, are measured by the standard hydrophone. The first ship is a large commercial ship cruising at approximately 20 knots and 3.2 km away from the hydrophone, while the second ship is 100 m away from the hydrophone. The results are used to study and analyze the recorded signals to obtain their spectral components for two purposes; to design the passive SONAR system of the AGUUV and test the ability of the AGUUV to detect, classify and track threats in the frequency bands of interest, and to design the proposed noise maker such that its noise spectrum has the same characteristics as the real targets. Three main noise sources of surface targets can be defined as propulsion noise, hydrodynamic noise and cavitation noise. Propulsion noise is that produced from engines, propellers, gears, turbines and other onboard mechanical auxiliary systems. Most of sounds produced by this source are in the band of 1 kHz and lower. The second type of noise is the hydrodynamic noise that is produced from the motion of the surface vessel in water. The sound from this source depends extensively on vessel speed. Whereas the band of this noise source can be few tens of Hertz for slow vessels, it can reach several hundreds of Hertz for fast vessels. The third type of SVN is that produced from cavitation occurs when air bubbles behind the propeller blow up. Cavitation noise is high frequency noise which can reach several tens of kHz [12-14]. Figures 3 and 4 show sound spectrum analysis for the recordings of the noise of the two example ships.

Figures 3 and 4 show that SVN has a strong acoustic power at wide bands of spectrum, from 0 Hz to 12 kHz. Also, it can be concluded that the first SVN example shown in Figures 3, has lower acoustic power than that of second SVN example shown in Figures 3. This can be explained due to the closer distance of the second SVN to the measuring device. Both of the two examples have higher spectrum power than the detection threshold (DT) of the passive sonar of the AGUUV at frequency band of 5 to 10 kHz.

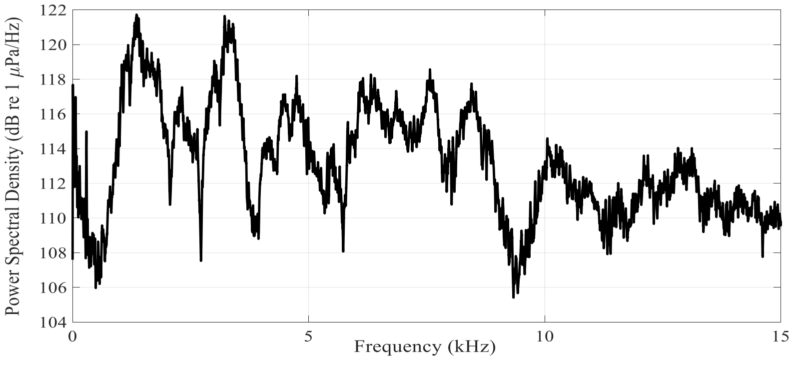

Figure 3. PSD of SVN from first example ship

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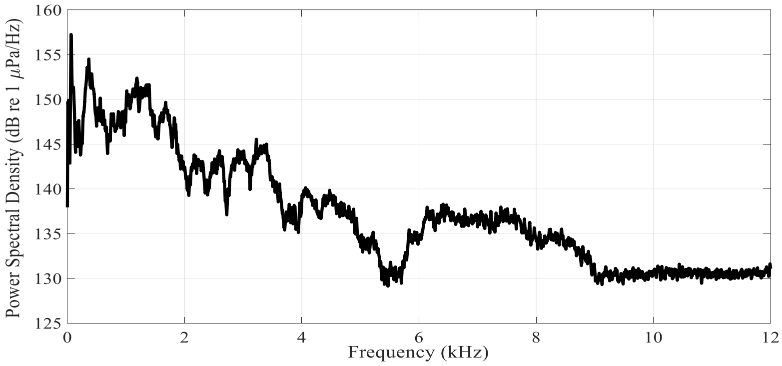


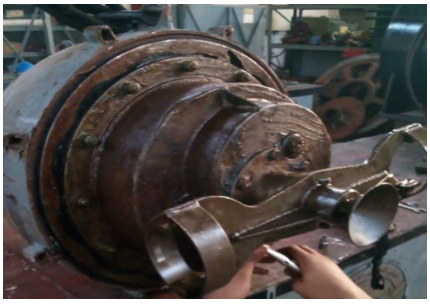
Figure 4. PSD of SVN from second example ship

3.2 Noise Makers and other Sound Generators

As sound waves are the main effector in Underwater Warfare (UW), several means of sound detection and generation are deployed by Navies and research centers. These means can be divided into two groups, measurement means and sound generators. Measurement means are performed by different types of sonar systems. On the other hand, some sound generators include Acoustic Mine Sweeper (AMS), Active Acoustic Decoy (AAD), Underwater Acoustic Target Training Simulators (UATTS) and Noise Makers (NM). Despite all members of second group can be considered as sound generators, they have different characteristics depending on their functions.

3.2.1 Acoustic Mine Sweeper (AMS)

The AMS is an old mean of sound generation that was towed behind mine sweeping platforms to activate Underwater Mines. One of our previously deployed AMS is shown in Figure 4. This AMS, is simply a large buoyant, D×L≈0.7m×2.15 m that contains a DC motor, gear train and two rotating balls. The DC motor is 4.4 KW power and its electrical supply, that was provided by the generator of the mine sweeper platform, is 220 VDC and 12 A. In the AMS the sound is generated when the two balls are forced to rotate in a clearance volume that permits impacting between the balls and the buoyant hull. It is found that the speed of the DC motor is 1500 rpm. Using simple analysis of sound generated by this AMS it is found that its spectrum characteristics is very close to that of surface vessel noise as explained in section 1.2. Figure 4 depicts some photos of AMS and its internal components. Figure (5a) shows the disassembled front part of the AMS and the arm with two caged cavities that contains two free to impact balls (not shown). Figure (5b) shows the DC motor that is inside the front part of AMS.



(a)

(b)

Figure 5. AMS photos (a) Front part. (b) DC motor.

The AMS is designed and built back in 1960s' when surface vessels were large in size and very noisy.

This explains why the AMS produces very loud noise whose amplitude is almost 183 dB re 1 μPa underwater.

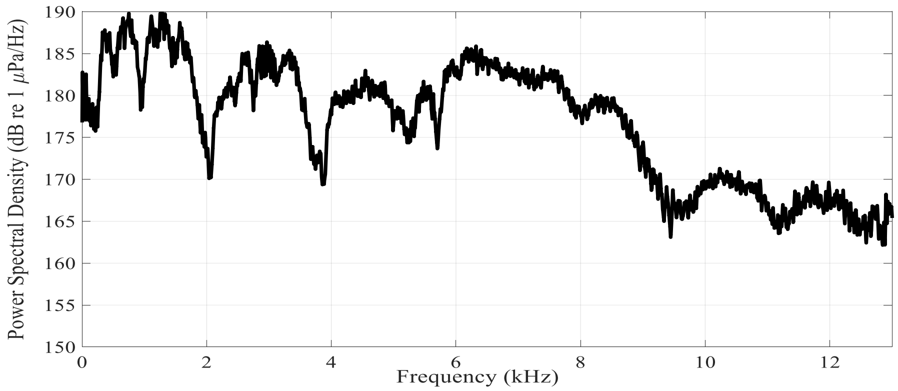


Figure 6. PSD of the AMS Noise

The analysis of the AMS sound in Figure 6 shows that it has high power of sound in both of low band of frequencies, from 1 Hz to 3 kHz and medium band from 6-9 kHz. Comparison between the AMS noise as shown in Figure 6 to SVN shown in Figs. 3 and 4 shows that noise of the AMS resembles that of SVN of example (1) at frequencies less than 9 kHz. The explanation of this difference at higher frequencies is the lack of cavitation noise produced by real ships' propellers while the AMS is just a towed buoyant that does not have a propeller. Comparing Figure 2 and Figure 6 shows that the noise of AMS has higher power than AGUUV self-noise in the frequency range of 5-9 kHz.

3.2.2 Noise Makers (NM)

At the beginning the AMS are used as NM to test the AGUUV. Using the AMS as NM has two disadvantages; the first is the limited number of the remaining items of the outdated AMS. The second disadvantage is the huge cost to prepare the target with a DC power source to provide the required voltage of 220 VDC and a starting current of 100 A to operate the AMS. So generally, the existing noise makers subject to obsolescence and malfunctions besides its use are not cost effective. For this purpose, a simple, low cost and locally available NM is needed for testing the AGUUV which is the main objective of the current work. Another NM from another supplier was used for testing AGUUV. It characterizes by its small size and simple design compared with the AMS despite it has the same principle of sound generation. The few available characteristics of this NM include its size, $D \times L \approx 0.08\text{m} \times 0.35\text{m}$, its low power consumption of 20 W which can be provided by any car battery. The available acoustic information is limited to its frequency band 5-10 kHz, and its sound power equals 133 dB re 1 μPa in water. This NM contains a 12 VDC motor that rotates some balls, and it had an audible sound very similar to the sound of high speed small motors. Other information about sound spectrum and sound power at frequencies higher than audible range is not available. However, it is expected that its spectrum may have large values of sound power at frequencies higher than 20 kHz.

4. In band Signal to Noise Ratio (SNR)

While being in passive search mode, AGUUV guidance system evaluates SNR of any target. To simulate this evaluation process, the recorded sound of AGUUV noise is taken as a noise signal, Y, and the recorded sound of both example ships and the AMS are used as targets' signals, X. Then, SNR for X with respect to Y is calculated by summing the squared magnitudes in the two different bands as in Eq. (1) [15]. The chosen bands are a low band that ranges from 50 Hz to 3 kHz and a high band that ranges from 6 kHz to 8.5 kHz.

$$SNR = 10 \times \log \frac{\sum_i \sqrt{X_i^2}}{\sum_i \sqrt{Y_i^2}} \quad . \tag{1}$$

Another valuable method of sound signal comparison is the Envelope Analysis Method (EAM) which is performed but out of the scope of this paper [16].

5. The Proposed Simple Design and Low-Cost Noise Maker (LCNM)

5.1 Design parameters and design constraints

The proposed NM should ascertain three acoustic design parameters and two main design constraints. The acoustic design parameters are the sound power, sound frequency and sound directionality. While the two design constraints are low cost and availability of all components.

5.1.1 Acoustic Design Parameters

The acoustic parameters for any NM should be specified with respect to the AGUUV type for which a training target is prepared. In current implementation of LCNM, three acoustic design parameters are considered as follows.

5.1.1.1 Sound Pressure Level (SPL)

The proposed LCNM is required to generate a sound that can be detected by AGUUV in its passive search mode. The recent deployed NM, described in section 3.2.2, that was used in preparation of a target for testing the AGUUV was very light in weight, consumes low electrical power about 20 W, and its SPL in water in the investigated frequency band is from 133 to 140 dB re 1 μPa at 1 m distance. Thence, the proposed LCNM is designed to produce an SPL > 140 dB.

5.1.1.2 Sound frequency

The documented frequency of a recently used modern NM is between 5 and 10 kHz. This is matching with results in previous sections which shows high SNR's of a target noise w.r.t AGUUV noise in the frequency range from 6 to 8.5 kHz.

5.1.1.3 Sound directionality

The AMS and modern NM are built as mechanical noise generator. The proposed LCNM is also designed to generate noise mechanically. In addition to its omnidirectional sound characteristics, a mechanical sound generator can be built with least cost and simplest design requirement. By comparing mechanical type noise generator with other types of sound generators, it is found that mechanical type is the simplest type that can guarantee two important characteristics that are required for testing AGUUV, omnidirectionality and wide band noise.

5.2 LCNM design and implementation

The proposed LCNM consists of a 4-inch steel cylinder and a ball-wheel that is a similar to the waterwheel. The balls-wheel is driven by a small 12 VDC motor which is a standard car cooling fan motor. The DC motor speed is 2000 rpm and its rated current is 8 A. The low amperage of the motor allows the usage of a car battery of 70 AH electrical capacity. This battery size is enough to run the LCNM continuously for more than 8 Hours. The balls-wheel is fabricated by welding two circular steel disks to the motor shaft. The two disks are 1 cm apart and 4 steel plates are welded vertically between the two disks to form four sectors. The balls-wheel have slightly smaller diameter than that of the cylinder to permit rotation of disks and prevention of steel balls from falling outside the four sectors. A spherical steel ball is put freely in each sector. The steel balls are free to rotate during the turning of the wheel while they are confined inside their sectors by the shell of the cylinder. The motor is fixed to the cylinder by welding two steel bases to both of motor casing and inner surface of cylinder. The positions of motor bases are adjusted such that the balls-wheel is near the center of cylinder length. The two ends of the cylinder are sealed well to inhibit any water leakage. One of the cylinder ends is holed for electrical cord and the other end is welded to an eye for hanging rope fixation. Figure 7 shows the cad drawing for the balls-wheel LCNM while Table 1 lists its main dimensions and used materials. Figure 8 shows two pictures for the DC motor with the balls-wheel and the assembled LCNM. The advantage of the proposed LCNM stems from its high performance, design simplicity, availability and low-cost of its components listed in Table 1.

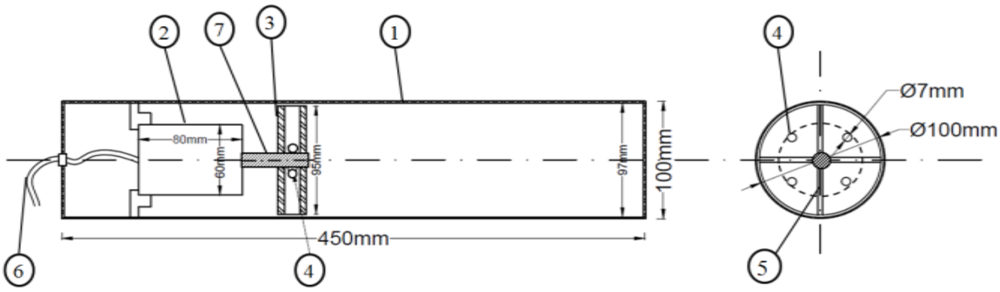


Figure 7. CAD drawing for LCNM

Table 1. list of illustrated parts breakdown for LCNM in Figure 6.

No.	Name	Dimensions	No.	Name	Dimensions and Material
1	Steel cylinder	D=100mm, L=450 mm	4	Steel balls	4 each D=7 mm
2	12 VDC motor 8 A, 2000 rpm	D=60 mm, L=80 mm	5	Steel ribs	4 Rectangles L=46mm,W=10mm
			6	Electric cord	2 mm
3	Balls wheel	D=97 mm	7	Motor shaft	5 mm

(a) (b)

Figure 8. (a) DC motor and balls-wheel, (b) Assembled LCNM.

6. Testing Methodology

Three types of tests were performed on the implemented LCNM, A lab test, and sea trials carried out with two tests; boat SONAR test and AGUUV sound detection and tracking test. In the lab test a standard hydrophone was used to record noise from LCNM. Then the recorded sound was analyzed and compared to other sources of noise; ships, AGUUV and the AMS. In the boat's SONAR testing, the LCNM was hanged in water from a boat that was about 1.5 km far from another boat that operates passive sonar system. The depth of the LCNM was 3 meters from water surface and the carrying boat is kept totally silence during the test. In the last test, an AGUUV was launched from a boat toward the silent boat that is hanging the LCNM. The distance between the two boats is 1.5 km.

The AGUUV uses its passive sonar in a medium band of frequencies from 5-40 kHz. Working in this band achieves high resolution and high SNR as it is far from the band of AGUUV self-noise. The used simple passive sonar system is an array of four discrete transducers with center-to-center separation of 7.5 cm. The normalized cross-correlation technique is used for signal identification and estimating the bearing of the sound source based on time-difference of arrival (TDOA).

7. Results

7.1 Lab test results

Figure 9 shows the experimental setup performed in the lab. The experimental setup consists of the sound source which is the LCNM placed in a water tank (the dimensions of the water tank are 3m×2m×2m), a standard hydrophone, DAQ, and a computer for signal processing. The radiated noise level and spectrum of LCNM are measured, recorded and analyzed by a standard hydrophone (its frequency response is 0.1 Hz to 100 kHz, and sensitivity -205 dB re 1 V/µPa) 1 meter from the sound source, the measured signals fed into a data acquisition system (DAQ) (DT9857E from DATA TRANSLATION), analyzed and processed by MATLAB code.

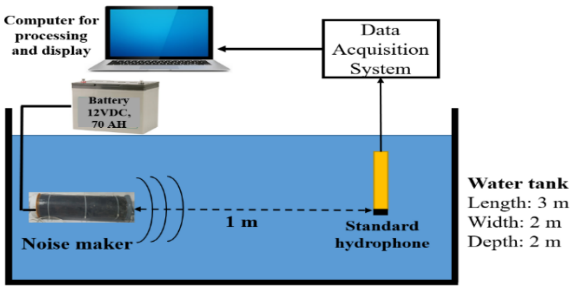


Figure 9. Experimental setup

Figure 10 shows that noise of LCNM has higher power in frequency band between 5-8 kHz than in 1-3 KHz band. The distribution of sound power shown in Figure 10 is preferable as it concentrates the majority of sound power in the band that is targeted by AGUUV SONAR. The sound pressure level of the measured radiated noise in water is greater than 120 dB re 1 µPa at 1 m distance.

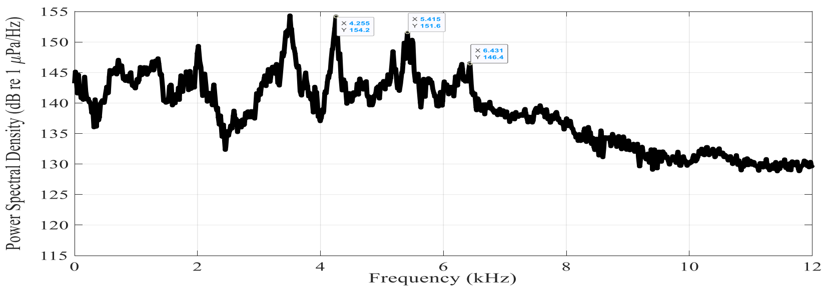


Figure 10. Lab PSD of the recorded noise of LCNM

7.2 Sea trials

The first sea trial is accomplished in the open sea by equipping the launching boat with a passive sonar to detect the LCNM at distance of 1.5 km as a target. The LCNM is hanged in water at depth of nearly 3 m from a silenced rescue boat. the launching boat's passive sonar has detected the LCNM where the ambient noise level is 35 dB re 1 µPa at 5 kHz measured at sea state 0.

The second test is accomplished during launching of the AGUUV. The AGUUV is launched from the launch boat 1.5 km away from the target (LCNM) toward the LCNM. The AGUUV could successfully detect the LCNM at 1.5 km distance from it. The in-band SNR is measured for the recorded LCNM sound. The SNR in low frequency band from 500 Hz to 3 kHz is -17 dB while it is 30 dB in high frequency band from 5 to 8 kHz.

8. CONCLUSIONS

This paper presents the implementation of a simple design and low-cost noise maker that was successfully used as acoustic target to test AGUUV systems before deployment. The proposed LCNM is a mechanical noise generator, omnidirectional, produces an SPL > 120 dB in water, consumes low power such that it can be run by car battery of 70 AH electrical capacity. The sea trials show that the AGUUV could successfully detect and track the LCNM with measured SNR =30 dB in high frequency band from 5 to 8 kHz. The introduced results confirm the ability of the proposed noise maker to simulate the acoustic signatures of the possible targets of the AGUUV and hence it can reliably test our AGUUVs prior to its deployment.

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