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Engineering an Electronic Shark Deterrent System Based Acoustic and EM Waves

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ABSTRACT: Acoustic/Electromagnetic (EM) waves are at the heart of numerous scientific tools and inventive technologies for plentiful state-of-the art applications. This study describes the design and implementation of a portable and effective acoustic and/or electromagnetic shark shield electronic system. In order to support shark deterrent technologies, a double-layer printed circuit board (PCB) circuit that includes a signal generator, pulse width modulation, and power amplifier modules has been designed. The 4-ohm, 3-watts loudspeaker was used in the construction of the acoustic shark shield system as a radiation element, while the EM system uses two electrodes and a wire antenna to produce EM wave radiation. The suggested design has then been subjected to a numerical analysis using the Multisim live demonstration circuit simulator. Lastly, a comparison between the experimental and numerical results was made. According to the findings, maximum peak-to-peak pulse amplitude of nearly 100 V and 55 Hz frequency was attained in a zero-meter distance deterrent system. These values are reduced to 53.2 V at approximately 55 Hz in the case of an EM shark system and with an artificial saltwater tank at 2 m distance, while the obtained peak amplitude for the acoustic shark deterrent system achieved peak-to-peak pulse amplitude value of almost 120 V at 55 Hz.

1. INTRODUCTION

Concerns throughout the world over the rise in shark attacks in recent years have drawn attention to the need for innovative ways to lower the risks connected with these attacks. The International Shark Attack File (ISAF) reported 120 shark-related deaths globally in the previous year, of which 22 were caused by provoked bites and 69 were unprovoked. This figure exceeds the five-year global average of six unprovoked deaths annually [1]. One famous occurrence was in Egypt, where a Russian citizen swimming in the calm Red Sea was attacked by a shark. This episode, like others, highlights how important it is to take immediate action to protect people from these dangerous predators. To solve this problem, a multimodal strategy that combines cutting-edge technology with knowledge of shark physiology and behavior is needed. Sharks have three semicircular canals that make up their inner ear. Within each canal are four sensory areas, one for sound and one for balance. Sharks can sense (or interpret) noises at frequencies between 10 Hz and 1 kHz; however, they are mostly sensitive to sounds at 500 Hz or below. The accurate frequency range that works best may vary based on things like the type of shark and features of the area where the deterrent is used. In light of growing worries about shark-human interactions, the use of acoustic technology as a shark deterrent could prove as an important solution to shield humans from sharks.

To produce an acoustic wave specially intended to scare off sharks, we will combine a pulse signal generator operating at 55 Hz with a power amplifier module and a loudspeaker system. Through the use of sharks' unique sensitivity to frequencies and sound patterns, this research seeks to present a novel approach that significantly reduces shark encounters in marine habitats. The configuration of the suggested pulse signal generator, amplification modules, and either concentrated sound emission or EM radiation is a novel application of technology in the field of shark deterrent. Table 1 provides a comparative examination of communications signal behavior with respect to various under water technologies [2, 3]. In [4], an electro shark shield (ESS) system including a series of power source, electronic components, system flowchart, antenna, and waterproof chase has been considered.

The device operates at 55 Hz and produces 5 nV/cm electric field strength; therefore, the shark catch by using this ESS system was 5.26% lower than other devices.

In order to reduce the chance of a shark bite, 80 and 150 V long-range electric deterrents systems are installed in [5]. An extensive region measuring 8 meters deep by 6 meters wide has been covered by both 80 and 150 V protection systems. In [6], types of developing shark shield technologies as well as their indicative cost of trailing shark deterrent have been presented.

To reduce the risk of shark bite incidents and fatalities, the New South Wales (NSW) Government provides a suite of bather protection measures on a 1 km New South Wales beach. A 1.67 Hz electro shark shield system with a voltage gradient peak of 100 V/m and a distance of 5 cm from the electrode sur-

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TABLE 1. Relative study of signal behavior with various under water technologies.

Parameters	Acoustics Communications	Optical Communications	EM/RF Communications
Force and back delay time	High delay time	Reasonable delay time	Low delay time
Data rates	Low data rates in Kbps	High data rates in Gbps	Moderate data rates in Mbps
Surface water	Influenced by multi-path propagation	Not affected	Not affected
Propagation Speed	Low	High	High
Propagation Distance	Long distance	Short distance	Short distance
Water state (Turbidity-suspended particles)	Influenced by water condition	Influenced by water condition	Not Influenced by water condition
Attenuation	Low-attenuation	Low-attenuation	High-attenuation
Cost	Need high cost to implement nodes	Need high cost to implement nodes	Need approximately low cost to implement nodes
Line of sight (LOS)	Not demanded	Highly demanded	Not demanded

face has been presented in [7]. This measured average voltage gradient gives a deterrent response equal to approximately 15.7 V/m which is enough to prevent shark attack. In [8], a 3 V/m electric field strength produced by five different electronic shark shield devices (shark shield freedom 7, shark shield freedom+ surf, shark shield Scuba 7, Rpela and no shark — dive version) are presented. The effective short-range deterrent distance achieved by each device is respectively $\sim$ 0.9: 1.1, 0.75, 0.7, 0.26: 0.45 and 0.24 meters.

Electric preventions toolbox of personal shark bite mitigation comprising Ocean Guardian's Freedom+ Surf and Freedom 7 electric deterrents devices has been considered in [9] for entirely eliminating bites from sharks. Ocean Guardian's Freedom+ Surf and Freedom 7 electric deterrents devices can partially reduce the risk of (bull, tiger, and white) shark bites for personal divers and surfers/swimmers by 54 : 69%. In [10], the effect of both anthropogenic and natural EM field emissions on marine creatures caused by the undersea high voltage direct current (HVDC) transmission cable is considered. A concrete effect has been observed on the bottom-dwelling sea creatures due to the emission of the EM field from subsea telecommunications and electrical power cables. In [11], white sharks can detect miniature EM fields less than 1 nV/cm. Thus using the EM fields, we can create an electric shark deterrent and reduce the probability of shark attacks. Different responses to electric shark shields over the bull sharks have been considered in [12], and Freedom+ Surf is now the most effective warning device for surfers and has the ability of reducing the risk of bull shark bite.

Sharks can sense EM fields surrounding a human in the water created by electrical deterrents, and they may react by stopping their progress toward the person. Two such deterrents, acoustic and EM Waves Shark Shields, have been examined in this paper. Individual electrical deterrents can differ in terms of the specific type of field such as pulse rate and the area of generated field. The electrical deterrents may only be reduced to a certain degree before they cease to produce an electrical field large enough to possibly scare off a shark.

The presented design addresses serious challenges in protecting swimmers, surfers, and divers from shark attacks with the following key contributions:

1. Hybrid acoustic and EM technologies have been combined with one electronic card to enhance the protection of the public from shark attacks.
2. Simple, cost-effective, and compact size design with commercially available electronic components along with very low power consumptions.
3. The proposed shark deterrent system can be deployed in underwater diving or swimming areas, on a boat (surfboard) and hangs on swimmer or divers bodies.

The structure of the article with different sections will be as follows.

In the next section, the system architecture is presented. The system methodology, which explains each electronic component of the deterrent system, is covered in the third section. The fourth section reviews block diagrams and proposed systems design. The execution of the suggested printed circuit board (PCB) for the two deterrent systems and their real responses are covered in the fifth section. Finally, the last section summarizes the work done.

2. SYSTEM ARCHITECTURE

One of the recommended frequencies, 55 Hz, can be produced by acoustic and EM waves for the purpose of shark deterrence, where the sensitivity of EM waves of the extreme optimum shark kinds is in the range of 55 Hz [4]. A method for lowering the average deliverable power of an applied electrical signal is called pulse width modulation, or PWM. Furthermore, the process is carried out by effectively splitting the signal into

FIGURE 1. Shark deterrent system style.

several segments. In order to achieve this control, PWM functionally modifies the average current and voltage it delivers to the load. Sharks have a keen sense of hearing and are sensitive to low-frequency sounds. They are able to follow sounds and particularly attracted to sounds made by wounded prey. Also, they gain thresholds with increasing frequency and have the most sensitive hearing at 20, 55, and 100 Hz [13]. Thus, shark shield systems make a range of personal deterrents with models designed for swimming, diving, and surfing, as shown in Fig. 1 [14].

Auditory perception is essential in bony fish. Sound has been linked to social behaviors in a number of animals, including territorial and reproductive acts. It has also been suggested that music may encourage social interaction. Additionally, the use of natural sound in navigation and predator and prey detection is made. A fish needs to be able to discriminate and recognize various noises in order to determine the type (predator or prey, for example) or location of these sound sources. Polymerous asperses, along with sound-producing electric fish and goldfish (Carassius auratus), are among the limited creatures that have demonstrated this capability. While several species of bony fish are more sensitive to disturbances from 20 Hz to 1 kHz, the majority of them can detect low frequencies up to 3 kHz [15, 16].

Sharks do not seem to make noise, yet like most of the bony fish, they are capable to identify the (directed) particle motion component of sound. A small opening on either side of their head provides direct access to the inner ear, where particle motion causes the cilia of the sensory hair cells in the ear to flex. In the end, this triggers a physiological response that results in the perception of sound. The second method to help sound detection is lateral line system [17]. In elasmobranchs, low-frequency sounds between 1 and 200 Hz can be heard by the lateral line, which is most sensitive between 20 and 30 Hz. The movement of cilia back and forth also initiates this system, which is classified as a short distance sensory system (one to two body lengths). Sharks are generally believed to be incapable of hearing the sound pressure component because they lack a swim bladder or other air-filled cavity to function as a pressure-to-displacement transducer. Nevertheless, two studies showed that two species are capable of detecting both particle motion and sound pressure: grey bamboo sharks and members of the tripterygiid family that do not have a visible pressure-to-displacement transducer. In our system, there are two crucial ways to communicate: acoustic and EM technologies [18].

3. METHODOLOGY

PWM signal generators, which can generate a pulse signal at 55 Hz, one of the ideal frequencies for frightening off sharks, are used to explore shark deterrents. An acoustic or EM wave is produced by a pulse generator module that consists of an electronic control circuit module supplied from two 9.0 volt lithium batteries with $-40°$F to $140°$F operating temperatures and a max discharge current of 0.8–1.2 Ah. Besides, wire antennas with two conductive square electrodes are used in the case of EM wave generation or a loudspeaker when the audio phase is produced. Exponentially decaying electrical pulses with peak amplitude and an inter-pulse period are then generated. A power amplifier equipped with TDA 2030 can deliver the highest power possible, enabling the signal to be strong enough.

3.1. Acoustic Technology

The acoustic techniques are especially attractive for changing the behavior of marine animals because sound waves may travel a greater distance than chemical, electrical, or optical cues. Sharks' auditory system consists of their two inner ears, which, like those of other fish, are responsible for identifying the particle motion component of sound.

Artificially generated noises with frequencies ranging from 20 Hz to 20 kHz are employed in shark deterrent devices to prevent both wild white sharks and captive epaulette sharks from attacking [17].

The omnidirectional hydrophone (Aquarian Audio H2a, manufacturer calibrated sensitivity value of 180 dB re 1 V/mPa; frequency range 0.01–100 kHz) and Audacity (v.2.4.2; 62) were used to measure the sound pressure levels of the experimental frequencies used in the experimental tank, which are 90 and 210 Hz as well as ambient sound (daily sounds from water in- and outflow, aeration pumps, protein skimmers, etc.) [18, 19]. In general, sound can travel through solids in other ways as well via other modes. As waves go across a medium, they may be reflected, refracted, or attenuated. This experiment aims to explore the effect of medium properties on sound. Whether sound travels through solid objects, liquid, or air, the medium it passes through has a significant impact on the route it takes. The medium's essential characteristics have an impact on how sound travels.

A sound wave's clarity and travel distance are determined by its intensity, or power per unit area. Long-range listeners can more easily discern higher-intensity sounds since they can travel farther without attenuating. The amount of energy per unit of time is called power. Hence, a sound wave's intensity is determined by the amount of power it transmits. With 68°F, sound travels through water substantially more quickly, with a speed of roughly 1482 m/s. Because water is denser and more incompressible than air, sound waves travel through it more swiftly and efficiently. Therefore, 55 Hz pulse is applied in the shark deterrent systems. Like sound waves in water, mechanical and sound waves travel across a medium by oscillating. Sound waves travel through water according to a number of critical factors, such as salinity, temperature, pressure, and density. These factors contribute to the unusual behavior of sound in aquatic environments, which is very different from the behavior of sound in the atmosphere [11, 20].

3.1.1. Signal Generator

As shown in Fig. 2, the module comprises eight separate keys that are used to adjust the duty cycle ratio and desired waveform frequency. It is fairly basic, has automated parameter saving, and supports both long and short presses to quickly increase or decrease a unit. Three-way duty ratio button that may be pressed simultaneously, real-time adjustment, liquid crystal display of the duty ratio of the last pressed button, and powerful real-time functionality make it possible to use as a basic multiple-road duty ratio scan.

FIGURE 2. Signal generator module.

3.1.2. Pulse Width Modulation (PWM)

As shown in Fig. 3, a PWM method is used to reduce the average deliverable power of an applied electrical wave form. Furthermore, the process is carried out by effectively dividing the signal into distinct segments. In addition, PWM controls the average current and voltage applied to the load. When a speaker employs PWM, the frequency of the signal influences the volume of sound generated. A higher pitch would be produced by a higher frequency and a lower pitch by a lower frequency. If the duty cycle was adjusted from 25% to 50%, the sound would variously produce different volumes. Consider that the speaker would produce more sound energy and run at a greater duty cycle (50%) for a longer period of time.

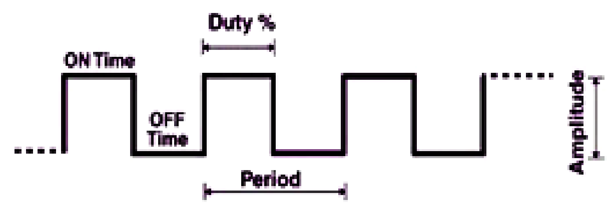

FIGURE 3. Pulse Width Modulation (PWM).

Less sound energy would be produced if the speaker ran at a shorter period of time where the generated pulse duty cycle equals 25% of the total cycle time. A PWM signal with a 50% duty cycle has equal durations of high and low states, thereby classifying it as a square wave. While changing the duty cycle without changing the frequency does not change the pitch of the sound, it does affect how the ear and brain interpret it. This is because square waves are composed of odd harmonics, which are essentially an infinite sum of sine waves. Generally, sharks can detect the pulses produced by electronic deterrent devices from a far distance and affected by them. Thus, shark shield electronic devices have the ability to attract sharks from a long distance before preventing them to approach divers, swimmers, and surfers when they are in close proximity [11].

3.1.3. Power Amplifier with TDA 2030

TDA2030 is a monolithic integrated amplifier designed to be used as a low-frequency class-AB amplifier, as illustrated in Fig. 4. Its typical output power is 14 W ($d = 0.5\%$) at 14 V/4 Ω load loudspeaker. The output power is guaranteed to be 12 W at a 4 Ω load and 8 W at an 8 Ω load (loudspeaker) at either ±14 V or 28 V DC sources. Its high output current and very low harmonic and crossover distortion make it ideal for 4-ohm or 8-ohm speakers. TDA2030A audio amplifier circuit is commonly implemented using a V-5-pin single in-line plastic package structure. The integrated circuit is widely used in car stereo receiver tape recorders, medium-power audio equipment, with

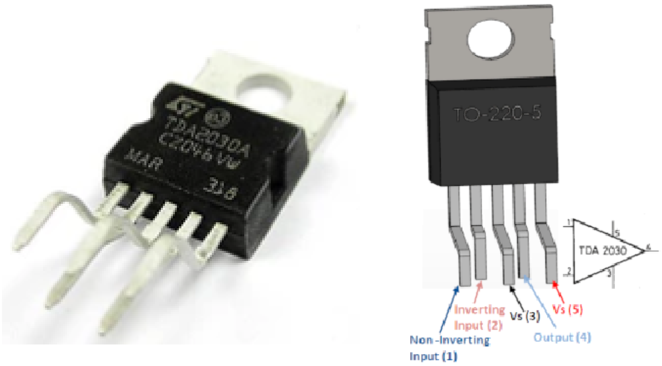

FIGURE 4. TDA2030 Class AB amplifier IC.

small size and large output power with minimum distortion value.

TDA2030 module has outputs that are both digital and analogue. It is able to estimate the loud level in the surrounding environment. This module is ideal for threshold measurement which indicates that if a user-set threshold value is surpassed, the sensor will immediately send out a digital high signal. However, as the rotary potentiometer directly affects the analogue signal, this also implies that the values obtained from analogue measurement are unsuitable for conversions.

3.1.4. Loud Speaker

As shown in Fig. 5, therefore, 4 ohm-3 watts loudspeaker is the most applicable loudspeaker for our proposed shark shield system. It is readily available in local markets as it presents low resistance to the passage of current at 55 Hz frequency. As the impedance decreases, the current increases which makes it ready to produce greater power for the loudspeaker. The power handling capabilities of the speaker which are rated as 3 watts, determine how much electrical power it can safely convert into sound energy without distortion. Lower frequency (55 Hz) demands less power for a 3-watt loudspeaker than the higher frequencies for the same observed loudness.

FIGURE 5. 4 ohm-3 watts loudspeaker.

3.2. Electromagnetic (EM) Technology

Since the 1960s, scientists have looked into the possibility of using sharks' electroreceptive qualities to keep humans away from them. It has been shown that exposure to intense (3 : 7 V/m) localized electric or magnetic fields deter sharks. This gave rise to the idea of creating repellents by using electric fields shark shield devices [21]. The electric field was generated through the previously mentioned signal generator, PWM and TDA2030 power amplifier besides the shark shield wire antenna and electrodes [4]. In fact, a number of elements, including wire thickness and length issues, must be carefully analyzed before designing the wire antenna.

1. Wire Thickness

- Resistance: Thicker wires and lower American Wire Gauge (AWG) numbers offer less resistance, which lessens power loss from heating and preserves signal amplitude. But our 2 mm^2 wire offers a compromise between handling and performance.

2. Wire Length

- Resistance: Longer wires have more resistance, which lowers the power supplied to the electrodes and causes voltage drops. To reduce resistance, we optimized the wire length to be ranged from 1 up to 2 meters.
- Increased capacitance and inductance in longer cables can also affect impedance and properties of the signal transmission, particularly at higher frequencies. By using a 1 m wire, we hope to reduce these effects and maximize signal transmission at 55 Hz.

3. Electrode Design

- The performance of EM shark deterrent devices is heavily influenced by the characteristics of electrodes. Enhancing the structure and materials of the electrodes can enhance the functionality of the device to ensure steady operation, reliable contact, and prolonged use. Optimal electrode performance relies on a range of properties, including mechanical, electrical (signal-to-noise ratio, medium impedance, conductivity), mechanical (adhesion, conformability), and environmental (corrosion, toxicity, biodegradability) factors [21].

We improved the design of our copper electrodes to boost signal transmission efficiency. Through thorough experimentation, we found that the most effective performance is achieved with square rectangular copper electrodes measuring 75 mm $\times$ 100 mm $\times$ 1.6 mm. This size guarantees a generous surface area, leading to enhanced conductivity and minimized resistance.

4. Attenuation, Phase Constant and Skin Depth of EM Waves at 55 Hz

- The attenuation coefficient, phase constant, and wave impedance estimates that emerge during wave transmission into saltwater are of our interest. It goes without saying that fresh water and seawater have very different salinities. Sodium chloride breaks down into Na+ and Cl-ions in water. Because they are charged, these ions will move in the presence of an electric field. Consequently, the primary reason for losses in saltwater is the conductivity associated with salt. The general expression for the

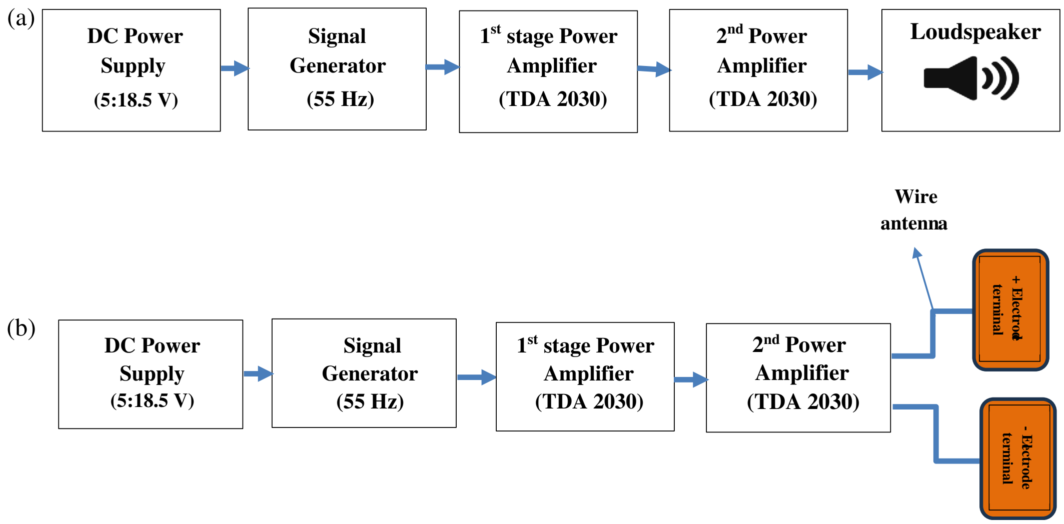

FIGURE 6. Block diagram for shark deterrent based on: (a) Acoustic Wave, (b) EM Wave.

propagation constant is calculated by the following formula [22]:

$$jk = j\omega\left(\mu\epsilon'\right)^{0.5} * \left(1 - j\frac{\sigma}{\omega\epsilon'}\right)^{0.5} = \alpha + j\beta \quad (1)$$

where μ and ϵ' are respectively the permeability and real permittivity values of the medium, while σ, ω, α, and β are the medium conductivity, angular frequency, wave attenuation, and phase constant, respectively.

We should be able to make several very good approximations to find α, β, and η in a sea water medium starting from the evaluation of the loss tangent using the value of $\frac{\sigma}{\omega\epsilon'} = 890 \gg 1$ and get,

$$jk = \left(-j2\pi f\mu\sigma\right)^{0.5} = \alpha + j\beta \quad (2)$$

$$\alpha = \beta = \left(\pi f\mu\sigma\right)^{0.5} \quad (3)$$

The depth of penetration which provides a useful parameter for understanding EM wave propagation in the seawater is then calculated by:

$$\delta = \left(\pi f\mu\sigma\right)^{-0.5} \quad (4)$$

At 55 Hz, the attenuation of EM waves in seawater is less severe than higher frequencies. The attenuation coefficient at this frequency can be calculated as described in Equation (3), where $\mu \approx \mu_0 = 4\pi * 10^{-7}$ H/m represents the space permeability, and the typical seawater conductivity σ is 4 S/m. Substituting these values in Equations (3) and (4), we get $\alpha = \sqrt{\pi * 55 * 4\pi * 10^{-7} * 4} \approx 0.0295\,\mathrm{m}^{-1}$, and the skin depth value is around 33.92 meters.

The velocity of propagation and the wavelength λ of EM Waves through sea water medium are then given by

$$v_p = \omega \times \delta \quad \& \quad \lambda = v_p/f \quad (5)$$

As seawater is denser than both pure and fresh water with density of 1.0 kg per Liter at 39°F) because of the dissolved salts, seawater has an average salinity about 3.5% (35 g/L, 35 ppt, 600 mM). It means that every kilogram (roughly one liter by volume) of seawater has approximately 35 grams of dissolved salts (mainly sodium (Na+) and chloride (Cl−) ions). Consequently, by calculating v_p and hence the corresponding wavelength at 55 Hz, we get a long wavelength equal to 213 meters which allows a deep penetration of EM waves into seawater at very low frequencies due to the conductive nature of this medium.

In our study, we used a 2 m length with a 2 mm wire diameter instead of a thicker wire, keeping the wire length and thickness factors described in Section 3.2 in mind.

4. DETERRENT SYSTEMS CONFIGURATIONS

The block diagram of overall acoustic and EM waves generator systems is plotted in Fig. 6. A DC power supply is adjusted to obtain an output voltage up to 18.5 V, which enabled the signal generator module's separate keys for adjusting the duty ratio and hence the operating frequency. The chopping up of the signal into discrete portions of 55 Hz frequency is then executed within the module itself, and the final required output pulses are obtained from PWM terminals. Consequently, the obtained pulses are amplified through the TDA 2030 power

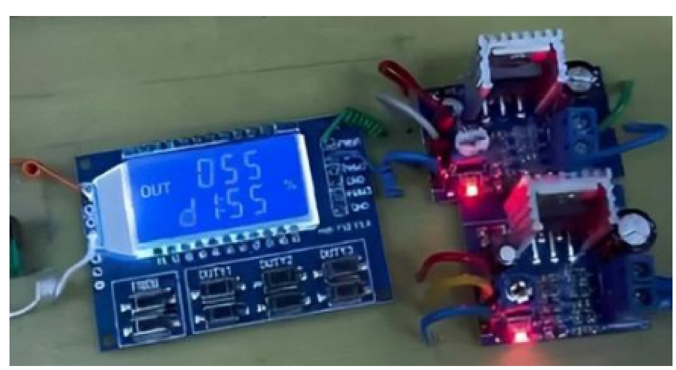

FIGURE 7. Prototype of the shark deterrent electronic system.

(a)

(b)

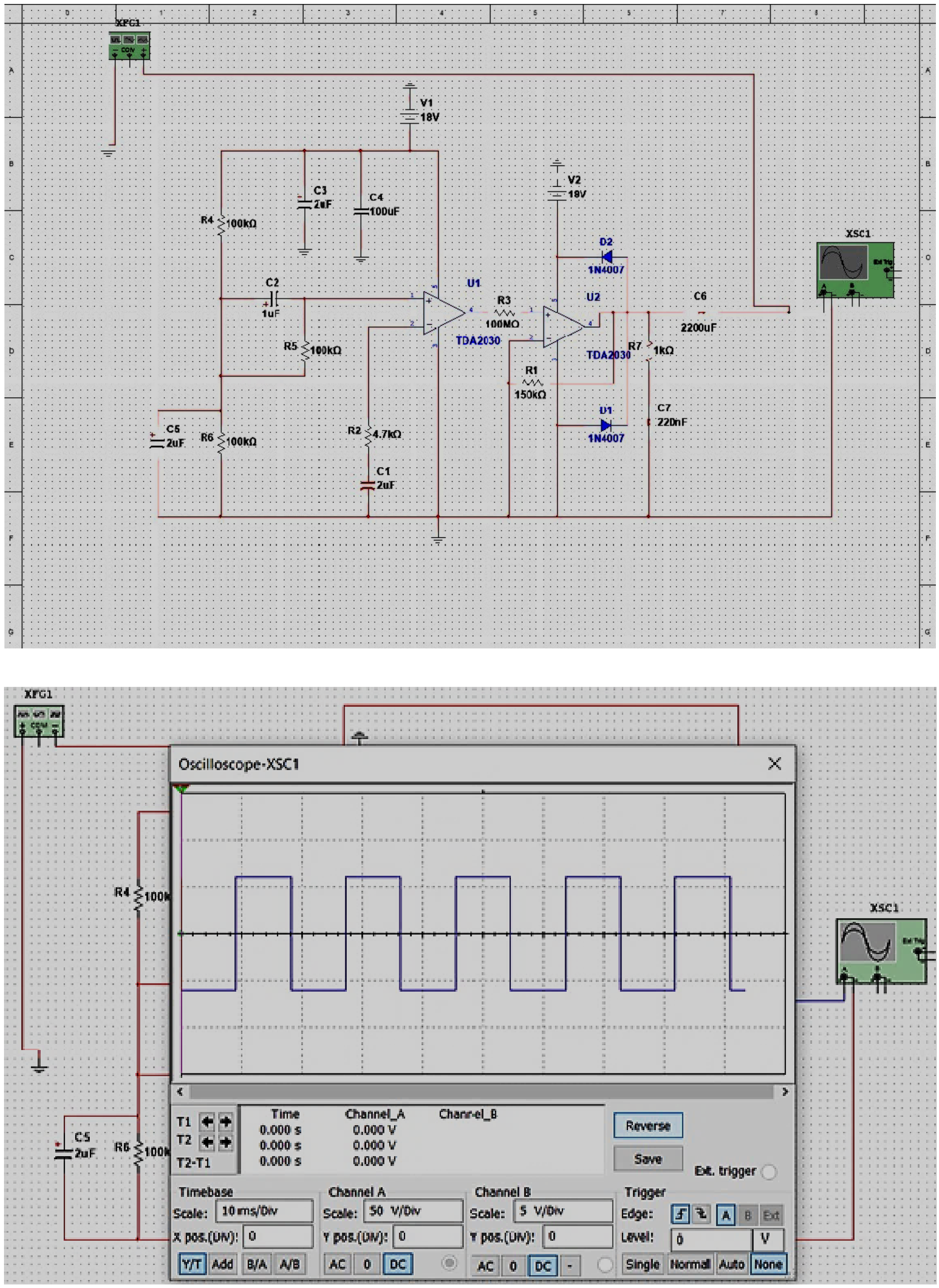

FIGURE 8. Multisim simulations for shark deterrent electronic system. (a) Circuit Multisim design. (b) Simulation results.

amplifier. The amplitude and pulse duration of the proposed design are then evaluated by means of a simulator and laboratory measurements through a PeakTech DC dual power supply 6210 and TBS 1102B-EDU digital oscilloscope.

The generated pulses are then transformed into acoustic waves by means of a DIN45500 (4 ohm-3 watts) loud speaker, which enables the transmitted wave to propagate through the seawater.

Conversely, Fig. 6(b) displays the EM shark deterrent system. The only difference between it and the acoustic module is that the EM version ended up with a wire antenna of +ve and −ve electrode terminals. Herein the operation of the EM deterrent system depends on the propagation of the EM wave with a 55 Hz frequency, which is produced and amplified with the same electronic components as the acoustic deterrent system.

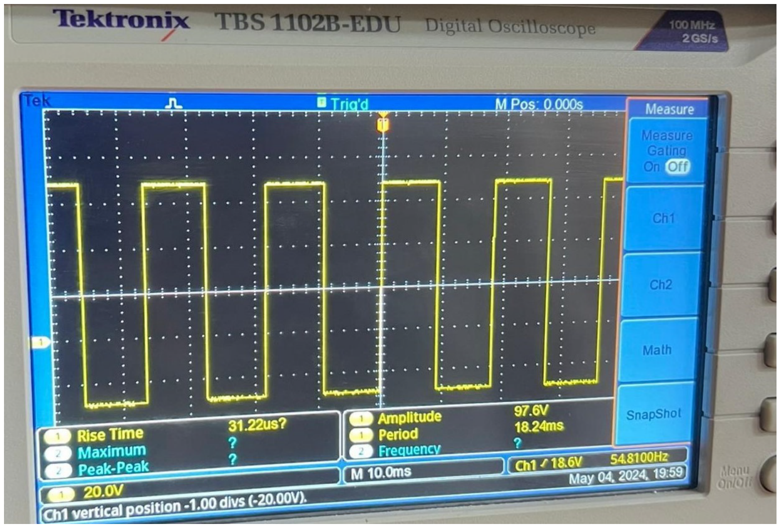

FIGURE 9. Experimental results for shark deterrent electronic systems at 0 m distance.

5. RESULTS AND DISCUSSIONS FOR THE DETERRENT SYSTEMS

Due to the perceptive analysis, an attractive shark deterrent electronic system by using the acoustic and EM wave is truthfully fabricated, where the proposed deterrent shield electronic card has been manufactured starting from the pulse generator and then the other electronic components, as depicted in Fig. 7. A DC power supply adjusted to produce up to 18.5 voltage which is connected to electronic card input terminals (the upper ends of the capacitors C3, C4 and resistors R4). Moreover, the input DC voltage is also feeding the positive power supply terminals of the two TDA2030 Class AB amplifier modules, while their negative terminals are connected to the ground as depicted in the circuit diagram shown in Fig. 8(a). The pulse generator module has been adjusted at half duty cycle in order to bring out a square wave operating at 55 Hz frequency. The two consecutive class AB power amplifier modules TDA2030 are dedicated to amplifying the wave form suitable for both acoustic/EM operating schemes.

Consequently, the physical parameters (pulse amplitude, duty cycle and frequency) for the electronic card are simulated by using a Multisim live demonstration circuit simulator. Therefore, the simulated results achieved the requirements available for the proposed design; the results showed that the achieved pulse amplitude is nearly 100 V peak to peak at 55 Hz operating frequency and a pulse width equal to 0.01 sec. as shown in Fig. 8(b).

The experimental results for the proposed electronic card are shown in Fig. 9. The manufactured electronic card produced a square pulse with maximum peak-to-peak amplitude of almost 100 V and 55 Hz frequency at no load in a 0 m distance. The results point out a good agreement between simulated and experimental measurements. As a result, the obtained pulse amplitude and frequency values are considered the calibration values that must be obtained before connecting the acoustic or EM components.

Finally, the deterrent system can be operated by connecting the ends of the electronic card to either a two-wire antenna with a 2-meter length and a 2-millimeter diameter, ending in two copper electrodes (EM scheme) or DIN45500 (4 ohm-3 watts) speaker terminals in an acoustic wave regime. The test setup is done by covering the manufactured electronic card and loudspeaker with a waterproof bag and then putting them in an artificial saltwater tank of dimensions 2 m $\times$ 2 m $\times$ 2.5 m, as shown in Fig. 10.

The manufactured electronic card and loudspeaker were supplied by either 11 or 18 V DC, which enabled acoustic pulses to propagate through the saltwater medium as displayed in Fig. 10(a). The currents drawn from the system are 0.004 A or 0.255 A in the case of inputs of 18 or 11 VDC, respectively. The image in Fig. 10(b) displays the generation of the electric fields accompanied by the connection of the electronic card via the wire antenna with $+$ve and $-$ve electrode plates 30 cm apart.

The electric field produced by the proposed system is within the range of commercially available Shark Shield Freedom 7 TM, where the electric field produced by the proposed system is within the range of commercially available Shark Shield Freedom 7 TM with an inter-pulse period of 0.6 s. Each pulse has a duration about 1.2 ms and a peak amplitude about 105 V (as measured in vitro in a tank filled with sea water) [11]. The experimental results confirmed that the proposed deterrent acoustic wave system provides exponentially decaying electrical pulses with a max peak-to-peak amplitude value of 119 V at almost 55 Hz operating frequency, as depicted in Fig. 11(a). The EM wave deterrent system is then made up of electronic components besides two electrodes, which produce output voltage decaying pulses of 53.2 peak to peak amplitude and approximately 55 Hz as shown in Fig. 11(b). Therefore, the prediction of shark threats can be increased using EM wave interaction properties in seawater as well as by acoustic waves in the desired operating frequency [11, 12]. Moreover, the EM fields induced during shark deterrent process are within the scope and will potentially affect the approach of sharks. The EM fields

(a) (b)

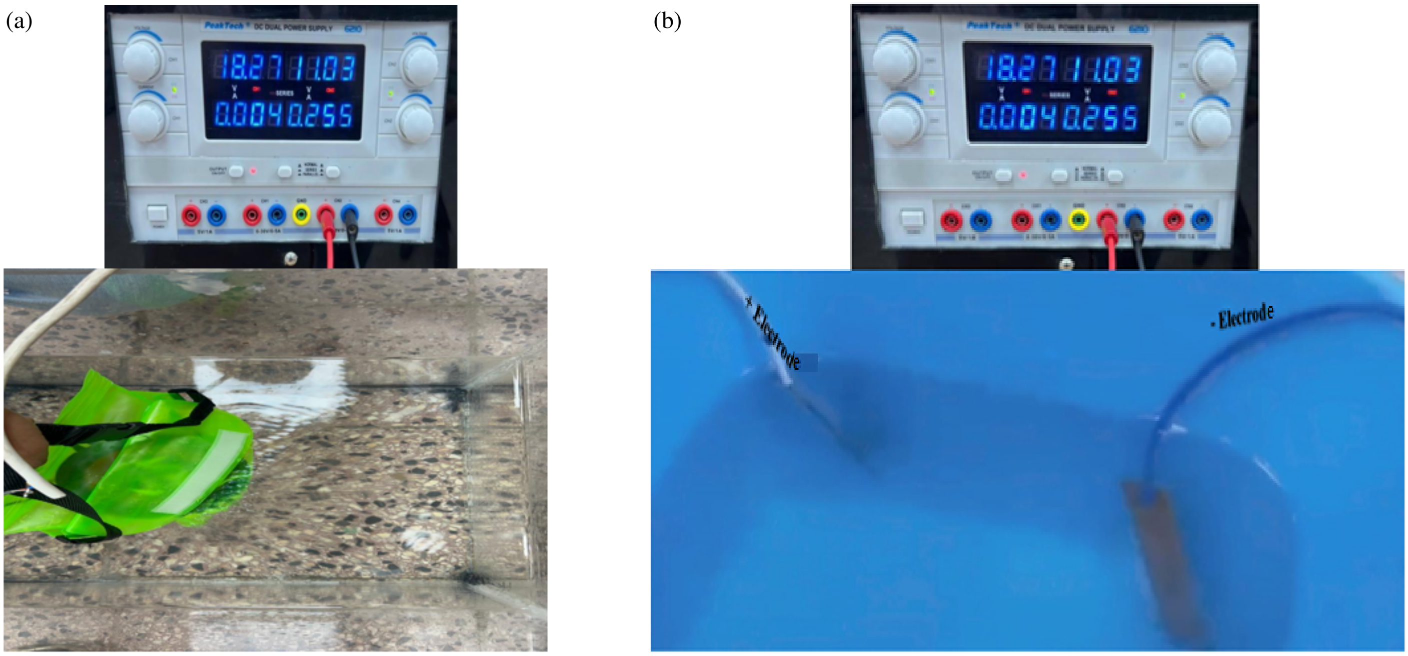

FIGURE 10. Experimental setup of a shark deterrent electronic system in an artificial saltwater tank fed by the DC power supply. (a) Acoustic wave, (b) EM wave.

(a) (b)

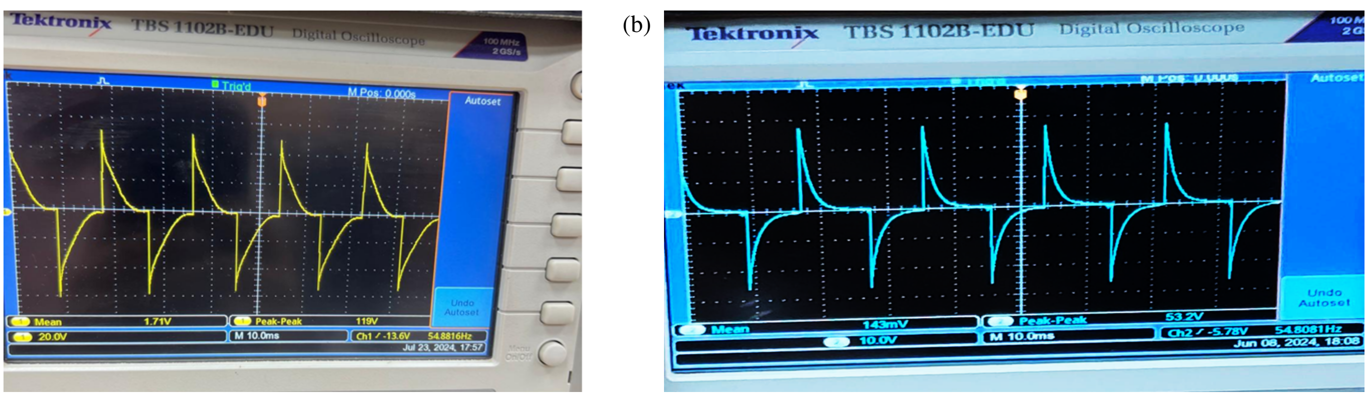

FIGURE 11. Experimental results for shark deterrent electronic system based on (a) Acoustic wave, (b) EM wave.

attenuate rapidly resulting in its shark shield effects limited to within a few meters from the shark deterrent electronic system. Exposures are also of fairly short duration that do not cause harm to non-target species [5, 23].

6. CONCLUSIONS

Several methods were employed to discourage sharks from getting close to people with the deterrence systems. In our study, we have developed a shark deterrent electronic system in two different electro-shield options: EM and acoustic shield techniques. The investigation's findings demonstrated that both tactics provide a potent deterrent against shark attacks. Shark sensitivity to acoustic waves and EM fields is illustrated by the utilization of both technologies to protect swimmers, divers, and surfers from shark bites. The needed standard values were reached by the obtained peak amplitude and duty cycle at both committed shark shield systems. The achieved peak-to-peak pulse amplitude is almost 120 V at 55 Hz and 53.2 V at almost 55 Hz for the acoustic shark and EM deterrent systems, respectively. In conclusion, hybrid acoustic and EM shark deterrent technologies have been combined with one electronic card to enhance the protection of the public from shark attacks.

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