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Advanced Layered Composite Structures for Underwater Acoustic Applications

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ABSTRACT

The detection of underwater objects is one of the most critical technologies, and there have been constant efforts for developing sophisticated sonar systems in naval warfare. Against such efforts, the countermeasure of hiding underwater vehicles, equipment and weapons is another technological challenge. One of the effective countermeasures against sonic detection for the submarines and other underwater objects, such as naval mines, is to employ composite/hybrid materials to prevent ease of detection. Geometrical forms, shapes and layers, along with the tuning of the acoustical impedance, lead to a considerable decrease of the sonar signals via absorption of the sonic waves. In this study, an original and novel design of multi-layered composite/hybrid structure was developed and underwater acoustic testing procedures of reflection, transmission and scattering were applied in 80 kHz-100 kHz frequency range. The findings obtained in this study showed that the multi-layered composite/hybrid materials with porous structure possess much lower values in millivolt than steel plates and might be potential candidates as covering and/or casing materials for underwater mines to reduce the acoustical signature against detection and identification.

Keywords: Underwater acoustical signature; Acoustical coating; Sea mines; Mine covers; Mine cases

1. INTRODUCTION

The detection of underwater objects is one of the most critical technologies, and there has been a sustained effort for developing sophisticated sonar systems in naval warfare. Against such efforts, the countermeasure of hiding underwater vehicles, equipment and weapons is another technological challenge[1]. The most fundamental example of such countermeasures is the “Alberich Coating,” which is a specialty rubber cladding that makes it difficult to be detected by sonar systems. “Alberich” was a code name inspired by the German mythological character that had the ability to become invisible. Alberich rubber layers made of specially designed composite/hybrid structure absorb the acoustical signals emitted by the sonars and effectively decrease the detection range[2,3]. Another effective countermeasure against the sonic detection for the submarines is to employ elastomeric cladding of the surface of the fuselage. Geometrical forms and shapes of the elastomeric layers, along with the tuning of the acoustical impedance, lead to a considerable decrease of the sonar signals via absorption of the sonic waves[4]. Other than the submarines, covering the mines using composite/hybrid materials to prevent ease of detection is another effective method in underwater warfare. Multi-layered composite/hybrid structures that are constituted by various geometrical forms, shapes and layers and the tuning of the acoustical impedance lead to a considerable decrease of the sonar signals via absorption of the sonic waves[5-8]. Theoretical background of using multi-component and multi-scale composite structures is reviewed extensively elsewhere[2,9].

It is underlined that complicated multi-component and multi-scale structures, such as laminated composite structures, filling components, and others are high-quality acoustic stealthy coatings for underwater objects. As an example, recently, anechoic composite structures with various components are being applied to the US submarine designs to meet the qualifications of silent submarines. In such structures, glass fiber reinforced polyurethane, butyl rubber composite double-layer anechoic structure was used to decrease noise by up to 40 dB[2]. Other than the United States, composite rubber acoustic coating is used by Germany as well[9]. A foam composite structure consisting of open-cell metallic foam embedded with polyurethane foam was investigated and evaluated for sound-absorbing properties by Cops[10], *et al.* They reported that the best performing composite foam increased the sound absorption by a factor of 6 (from .1 to .6) in the low-frequency test range and by a factor of 2 (from .2 to .4) broadband compared to the original metallic foam. Wang[11], *et al.* presented their investigations on a sound-absorbing periodically arrayed structure with carbon fiber honeycomb combining two sound absorption mechanisms of cavity resonance and impedance transition loss. They indicated that the experimental, theoretical and simulated absorption coefficient match well to verify the reliability of fabrication procedures for the polyurethane composite array supported by carbon fiber honeycomb. It is found that the fabricated structure with carbon fiber honeycomb achieves 0.9 absorption bandwidth under hydraulic pressure of 1.5 MPa at 2.400-10.000 Hz. They also underlined that broadband sound absorption is achieved for water depths up to 300 m, which suggests that the structure with carbon fiber honeycomb may have practical applications

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on submarine noise insulation layers and anti-sonar detection in the near future. As for the composite sandwiched structures for underwater sound absorption usage, Li[12], *et al.* used rubber plates, micro-perforated panel (MPP) and castor oil in their study. The effects of the structural components and the micro-perforated panel parameters are studied, and the theoretical result results were in good agreement with the experiments. The MPPRC structure can enhance the absorption performance compared with the equal-thickness rubber.

In this study, specifically designed composite/hybrid panels are investigated in the underwater acoustic testing systems for the measurements of the absorbing, transmitting and emitting capabilities of acoustic waves. The results of such novel complex forms and structures as covering and/or casing materials are evaluated for the application in underwater countermeasures against the acoustical detection of mines and other objects.

2. MATERIALS AND METHODS

2.1 Materials Selection

Sea mines are self-contained explosive devices and widely available, effective and damaging weapons which have been in use for many years in naval warfare. They are inexpensive and easily produced and planted in naval operations and offer a practical early warning system[13,14]. Recently, the casing of such naval mines using a variety of cover materials to prevent sonar detection is an important issue for naval warfare. Such materials for mine casing may not necessarily cover all range of acoustic frequencies and conditions to render acoustical stealthiness. In underwater conditions, there are many parameters affecting acoustical properties, such as thickness, form, geometry, porosity, density and frequencies.

Although such materials like elastomers, polymers and neoprene are already used to prevent underwater stealthiness, there have been very limited literature and information that include experimental data on innovative materials development to decrease the underwater acoustic signature for 80kHz-100kHz scale[15].

A novel design of layered composite/hybrid structured material with decreased acoustical signature for underwater applications is developed specifically as the covering and or casing for naval mines[16,17]. Figure 1 demonstrates the schematic structure of this design. Rubber plates are used as an outer cover. Composite honeycomb structure with silicon and granulated glass and metal powders as fillers are utilised along with their acoustical functions to decrease acoustical signature. Layered panels with the dimensions of 50 cm x 50 cm x 2 cm are tested in the underwater acoustic testing pool.

3. UNDERWATER ACOUSTIC TESTS

In general, impedance tubes, acoustical testing pools and natural ponds, small lakes, marine environments are employed to measure acoustical properties and characteristics[1,18]. A wide range scale of acoustical frequency bands is used in the natural marine environment, ponds, small lakes and acoustical testing pools, while a very limited scale of frequency bands is possible in impedance tubes. In this investigation, an acoustical testing pool, as shown in Fig. 2 with the dimensions of 4 m depth, 8.2 m length and 4.2 m width is employed.

3.1 Frequency Ranges

In principle, mine countermeasure operations are based upon the following steps: Tracking, detecting and deactivation of any kind of underwater mines[19]. This process is achieved in four basic phases:

(i) Detecting
(ii) Classification
(iii) Identifying and

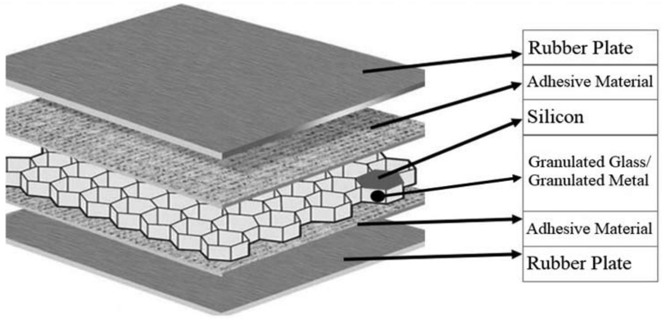

Figure 1. Rubber cladded honeycomb structured plates.

Figure 2. Acoustical testing pool.

(iv) Demolition. Mine detection sonars are used in the identification phase.

In this regard, frequency ranges of mine detection sonars are evaluated for this study and the most used frequencies will be 80 kHz, 90 kHz, 95 kHz and 100 kHz are determined to be the reference frequencies[20].

3.2 Acoustical Testing Set Up

The underwater acoustical set up consists of a transducer and five hydrophones, as shown in Fig. 3.

The signal generator produces short acoustical pulses in predetermined frequencies and propagated acoustical signals are recorded as separate RMS values in millivolts via oscilloscope through the currencies formed on hydrophones.

The centers of plates are positioned and locked above 2 m of the pool's bottom[21]. Hydrophone #1 is positioned in front of the plate along a line through the center of the plate and perpendicular to the plate. Hydrophones # 2 and #3 are just in the back of the plate and positioned perpendicular to the center. The hydrophone #4 and #5 are located along lines through the center and making angles in 60° and 30°, respectively, with the plate vertical axis. Figure 4 reveals the locations of the hydrophones, plates and transducer inside the acoustical testing pool.

4. ACOUSTICAL MEASUREMENTS

Dominant material for the underwater weapon systems is stainless steel in various dimensions. Therefore, a stainless steel plate of 50 cm x 50 cm x 2 cm dimension is employed as the reference plate. Firstly, the reference steel plate is located in the positions shown in Figs. 3 and 4 and acoustical measurements with the predetermined frequencies are conducted and recorded. Thereafter, the measurement on the layered composite/hybrid plates is achieved. Reflection from hydrophone #1, transmission values from hydrophones #2 and #3, scattering values in 60° and 30° from hydrophone #4 and #5, respectively, are measured and recorded.

4.1 Measurements on the Reference Steel Plate

Acoustical measurements are conducted on the reference stainless steel plate of 50 cm x 50 cm x 2 cm dimension in predetermined reference frequencies and tabulated in Table 1.

Figure 3. Acoustical testing set up inside the pool.

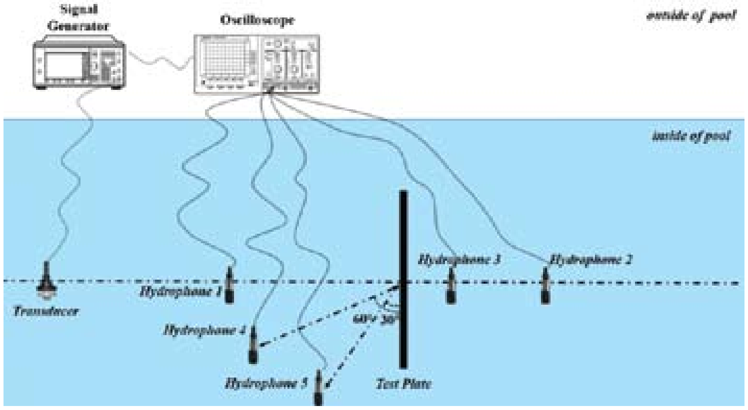

Figure 4. Locations of the signal generator, oscilloscope, transducer, hydrophones and the test plate.

4.2 Measurements on the Plates Containing Glass Granules

Acoustical measurements are conducted on the plate containing glass granules of 50 cm x 50 cm x 2 cm dimension in predetermined reference frequencies and tabulated in Table 2.

4.3 Measurements on the Plates Containing Metallic Granules

Acoustical measurements are conducted on the plate containing metallic granules of 50 cm x 50 cm x 2 cm dimension in predetermined reference frequencies and tabulated in Table 3.

Table 1. Measurements on the reference steel plate

	80kHz	85kHz	90kHz	95kHz	100kHz	Av
	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)
Direct measured value at Hydrophone's outlet with the Hydrophone 1	430.0	402.0	424.0	461.0	411.0	425.6
Hydrophone 1 (Reflection)	235.0	165.0	118.0	98.2	91.5	141.5
Hydrophone 2 (Transmission)	99.0	80.9	38.8	50.3	31.6	60.1
Hydrophone 3 (Transmission)	103.0	69.8	65.3	49.1	45.8	66.6
Hydrophone 4 (Scattering at 60°)	57.3	89.0	101.0	76.2	52.7	75.2
Hydrophone 5 (Scattering at 30°)	44.7	74.0	29.6	13.7	21.6	36.7

Table 2. Measurements on the plates containing glass granules

	80kHz	85kHz	90kHz	95kHz	100kHz	Av
	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)
Hydrophone 1 (Reflection)	45.00	25.60	45.20	52.00	55.00	44.6
Hydrophone 2 (Transmission)	10.50	3.80	5.70	6.20	13.70	8.0
Hydrophone 3 (Transmission)	5.52	3.20	6.06	3.70	2.20	4.1
Hydrophone 4 (Scattering at 60°)	23.30	34.60	26.10	18.60	16.00	23.7
Hydrophone 5 (Scattering at 30°)	44.60	72.20	29.10	13.20	19.00	35.6

Table 3. Measurements on the plates containing metallic granules

	80kHz	85kHz	90kHz	95kHz	100kHz	Av
	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)	Amplitude (mV)
Hydrophone 1 (Reflection)	77.50	66.00	60.00	56.60	48.50	61.7
Hydrophone 2 (Transmission)	14.50	13.20	13.00	4.91	4.54	10.0
Hydrophone 3 (Transmission)	4.82	2.50	1.94	3.38	2.36	3.0
Hydrophone 4 (Scattering at 60°)	21.70	10.50	10.10	24.40	11.90	15.7
Hydrophone 5 (Scattering at 30°)	43.00	59.50	30.10	19.90	12.40	33.0

5. RESULTS AND DISCUSSION

Acoustical measurements are initiated first on the reference stainless steel plate. Thereafter, other layered composite/hybrid plates are positioned in the same location and acoustical testing proceeded accordingly. During the exchange of the plates, fluctuation and bubbling occurred inside the testing pool and currency measurements on hydrophones were difficult to hold the balance. Following the stabilisation of currency values on the oscilloscope, measurements are started to be recorded.

5.1 Reflection Measurements on Hydrophone # 1

Measured reflection data as millivolts on hydrophone # 1 based upon the acoustical tests on the reference steel plate and other plates are shown in Fig. 5.

Reflection values are varying for each applied frequency on the plates. It is observed that the reflection on the plates containing glass and metallic granules is lesser compared to the reference steel plate. The smallest reflection values are recorded in 85 kHz frequency measurements. Higher reflections are recorded on the plates containing metallic granules at 80 kHz, 85 kHz and 90 kHz compared to the plates containing glass granules.

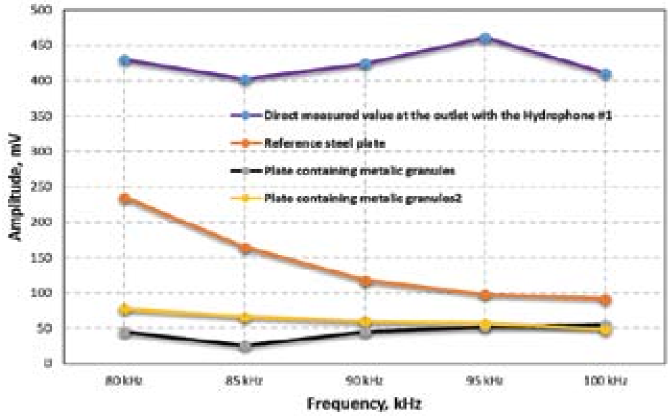

Figure 5. Reflection measurements on hydrophone # 1.

5.2 Transmission Measurements on Hydrophone # 2

Measured transmission data as millivolts on hydrophone # 2 based upon the acoustical tests on the reference steel plate and other plates are shown in Fig. 6.

As can be seen, transmission values are varying for each applied frequency on the plates. It is observed that the transmission values on the plates containing glass and metallic granules are lower compared to the reference steel plate. Smallest transmission values are recorded in 85 kHz frequency measurements. The data revealed that metallic and glass granules have similar effects on transmission values.

5.3 Transmission Measurements on Hydrophone # 3

Measured transmission data as millivolts on hydrophone # 3 based upon the acoustical tests on the reference steel plate and other plates are shown in Fig. 7.

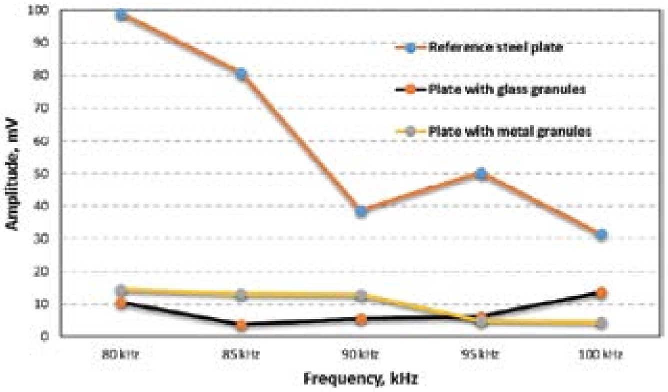

Figure 6. Transmission measurements on hydrophone # 2.

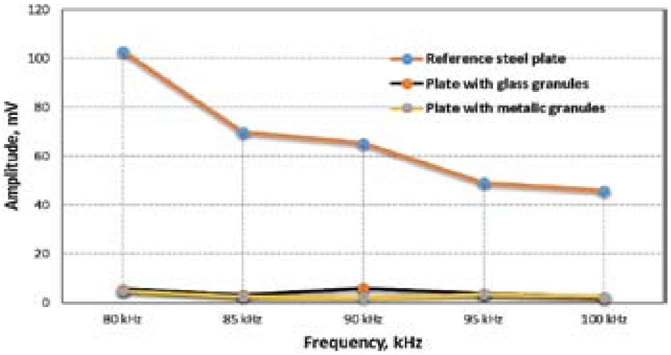

Figure 7. Transmission measurements on hydrophone # 3.

As can be seen in Fig. 7, transmission values are varying for each applied frequency on the reference steel plate. It is observed that the transmission values on the plates containing glass and metallic granules are lesser compared to the reference steel plate. The data show that metallic and glass granules have similar effects on transmission values. Comparisons of transmission data for the hydrophones # 3 and # 2 reveal lesser values for the hydrophone #3 since it is located much closer to the plate. Reflection by the pool's walls, different locations of hydrophones or porous structure of the plates with glass and metallic granules may result in such difference.

5.4 Scattering Measurements on Hydrophone # 4 at 60°

Measured scattering data as millivolts on hydrophone # 4 at 60^o based upon the acoustical tests on the reference steel plate and other plates are shown in Fig. 8.

Scattering values are varying for each applied frequency on the plates. It is observed that the scattering values on the plates containing glass and metallic granules are lesser compared to the reference steel plate. The data show that metallic and glass granules have similar effects on the scattering values, with the exception at 85 kHz.

5.5 Scattering Measurements on Hydrophone # 5 at 30°

Measured scattering data as millivolts on hydrophone # 5 at 30^o based upon the acoustical tests on the reference steel plate and other plates are shown in Fig. 9.

As can be observed in Fig. 9, scattering values are varying for each applied frequency on the plates. It is observed that the scattering values very close and similar for all the plates containing glass and metallic granules and the reference steel plate. The data show that metallic and glass granules have similar effects on the scattering values at 30^o. The difference in the scattering data may be due to the varying positioning of the hydrophones.

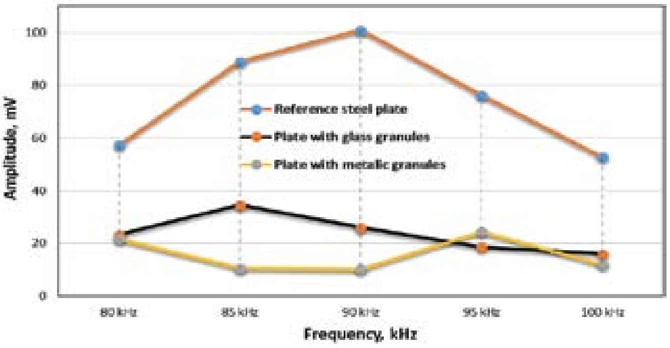

Figure 8. Scattering measurements on hydrophone # 4 at 60°.

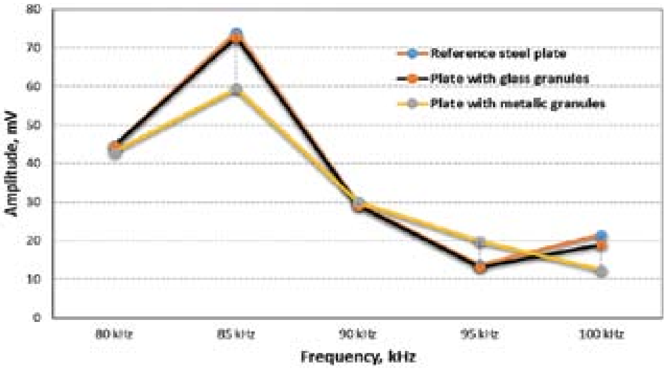

Figure 9. Scattering measurements on hydrophone # 5 at 30°.

The data given in Tables 1-3 is summarised in Table 4. In this, the data comparing reflection, transmission and scattering at 60^o and 30^o measurements for two types of composite plates is given along with the % difference with the reference plate. As for the reflection measurements, composite plates with glass granules result in 68.4% decrease in reflection compared to the reference steel plate. On the other hand, composites with metallic granules indicate 56.3% decrease. As for the transmission measurements, composite plates with glass granules result in 86.6% and 93.8 % lower values compared to the steel reference plate. Meanwhile, composite plates with metallic granules give 79.1% and 94.49% lower values which are almost identical decreases in transmission for both of the composite plates. As for the scattering measurements at 60^o and 30^o, composite plates with glass granules result in 68.4% and 2.99% lower values compared to the steel reference plate. Sound absorbing performances revealed as lower reflection,

Table 4. Data comparing measurements against reference steel plate

	Av Ref.Steel Pl.	Av Gla.Gr	% Difference w/ref.steel pl	Av,Met Gr	% Difference w/ref.steel pl
	Amplitude (mV)	Amplitude (mV)		Amplitude (mV)	
Hydrophone 1 (Reflection)	141.5	44.6	68.4	61.7	56.3
Hydrophone 2 (Transmission)	60.1	8.0	86.6	10.0	83.36
Hydrophone 3 (Transmission)	66.6	4.1	93.8	3.0	95.49
Hydrophone 4 (Scattering at 60°)	75.2	23.7	68.4	15.7	79.1
Hydrophone 5 (Scattering at 30°)	36.7	35.6	2.99	33.0	10.08

Ref.Steel Pl.-Reference Plate; **Gla.Gr.**-Glass granules; **Met.Gr.**-Metallic granules transmission and lower scattering at 60° are due to porous characters of granules and scattering over granular shapes. Meanwhile, composite plates with metallic granules give 83.6 % and 10.08 % lower values in which the differences in case of scattering at 30 ° are insignificant for both kind of plates.

As pointed out before, coatings on US submarines designed with glass fiber reinforced polyurethane, butyl rubber composite double-layer anechoic structure was used to decrease noise by up to 40 dB[2]. In this regard, the decrease of reflection by 97 mV and 79 mV with the glass and metallic granules respectively should be considered as better sound absorbing performances. As for the results reported by Wang et al. on arrayed composite structure with carbon fiber honeycomb it is found that the fabricated structure with carbon fiber honeycomb achieves 0.9 absorption bandwidth under hydraulic pressure of 1.5 MPa at 2400-10000 Hz[11]. Such sound absorbing performance data is also comparable with the transmission measurements resulting in 83-95% decrease compared to the steel plate.

There have been very limited investigations conducted on such complex, multi-layered composite structures. In one of the studies, using a honeycomb structure filled with polyurethane and contains alumina powders, which are attached to an aluminum plate and covered with stainless steel foils, it is indicated that such structures are highly technological. Such complicated structures are extremely difficult to be modelled due to a variety of complex interfacial surfaces and junctions within the structure[2,9]. Very recently, investigations on the various complex composite systems have started to be published covering the sound absorption performances of such multi-scale and multi-layered composites[10-12]. In an interesting paper, Fu et al. reported an investigation using nanotechnology to develop sound absorption materials for underwater applications. Nanocomposite of carboxyl functionalised multi-walled carbon nanotubes (MWCNT-COOH) is utilised as additives into polydimethylsiloxane (PDMS) with a dispersant to enhance the underwater acoustic properties. Sound absorption coefficient in the low-frequency range from 1.500 Hz to 7.000 Hz improved to 0.3 with the addition of MWCNT-COOH[22]. Even such recent publications on the underwater sound absorption studies on the complex composites structures may not necessarily yield into direct comparative evaluation with this current study. In this regard, the novelty and originality of the multi-layered composite structure designed and fabricated through this study may attract further interest in future underwater sound absorption studies.

6. CONCLUSION

Underwater stealth technologies for naval mines are possessed by advanced navies and considered as a critical force multiplier due to the strategic effects that they can create in the operation area. There have been very limited literature and information that include experimental data on the innovative materials development for decreasing the underwater acoustic signature. Also, a detailed comparison cannot be hold between the novel and the innovative design of layered composite/hybrid structure, and such materials are already in use because of insufficient experimental data for the 80kHz-100kHz scale.

In this respect, the original, novel and innovative design of layered composite/hybrid structures and their underwater acoustical tests show the importance of this investigation.

Based on the data recorded through the underwater acoustic testing procedures, the following remarks can be concluded and summarised:

(i) An original and novel design of multi-layered materials with porous structure resulted in lesser underwater acoustic transmission, scattering and reflection, which may be employed for effective acoustical signal reducing purposes.

(ii) It is found that the plates lead into varying results for varying frequencies indicating property changes with differing frequencies. Reflection by the pool's walls, different locations of hydrophones or porous structure of the plates with glass and metallic granules might result in such difference.

(iii) During the exchange of the plates, fluctuation and bubbling occurred inside the testing pool and currency measurements on hydrophones were difficult to hold the balance. Following the stabilisation of currency values on the oscilloscope, consistent measurements were started to be recorded.

In conclusion, an original and novel design of multi-layered composite/hybrid structure is developed and underwater acoustic testing procedures of reflection, transmission and scattering were applied in 80 kHz-100 kHz frequency range. A steel plate was used as the reference plate for the evaluation of reflection and scattering performances. It is found that the multi-layered composite/hybrid materials with porous structure have much lower values and maybe a potential candidate as a cover and/or case material for underwater mines to reduce the acoustical signature against detection and identification.

Future research should further develop and confirm these initial findings that include experimental data for the 80kHz-100kHz scale by making a comparison between different types of structures.

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CONTRIBUTORS

Dr Barış Şahiner received his PhD from Gedik University, Istanbul, Turkey in 2019. Currently he is working in the Turkish Navy as Lieutenant Commander. He has one national patent (pending) in the design of composite systems. His research areas are naval mine warfare, underwater stealthy structures and composite structures for defence applications.

In the current study, he was involved in experimental work for acoustic measurements, acoustic test set-up, design of materials and writing the manuscript.

Prof. Sunullah Ozbek received the BSc in Materials Engineering from the Istanbul Technical University, Turkey, in 1974, and the MSc and PhD in Materials Science and Engineering from the Swansea University, Wales, United Kingdom, in 1978 and 1984, respectively. He is currently working as a Professor in the Department of Mechanical Engineering, at Dogus University. His research areas include Nanomaterials, Composite Processing, Underwater Acoustic Stealthy Structures, and their Applications in Defense and security.

In the current study, he involved in the supervision of the whole investigations, design of the materials' system, guiding and supervising the experimental tests, partly writing and editing the manuscript.

Prof. Tarik Baykara received his PhD from Rice University, Houston, U.S.A. Currently, he is teaching as a full-time professor in the Mechanical Engineering Department of Dogus University, Istanbul, Turkey. He published 92 research papers in international journals and he has four patents (1 certified, 3 pending) in the design of composite systems. His research areas are composite design, processing and testing, technical ceramics and powder metallurgy, and also hard cermet systems in particular.

In the current study, he involved in the design of the materials' system, guiding and supervising the experimental tests, partly writing and editing the manuscript.

Mr Alparslan Demirural graduated from the Turkish Military Academy. Currently, he is working as a chief technological research associate in the Advanced Mechanical Technologies Laboratory of the Doğuş University of Turkey. His research areas are composite processing, product developments and applications on armour and underwater vehicles.

In the current study, he involved in the development of the anechoic composite materials, supervising the experimental tests, partly writing and editing the manuscript.