Defence Science Journal, Vol. 69, No. 6, November 2019, pp. 607-612, DOI : 10.14429/dsj.69.13337

Towed Acoustic Countermeasures for Defending Acoustic Homing Torpedoes

Jomon George*, P. Sinchu, K. Ajith Kumar, and T. Santhanakrishnan

DRDO-Naval Physical and Oceanographic laboratory, Kochi – 682 021, India
**E-mail: jomong@npol.drdo.in*

ABSTRACT

The growing torpedo threat to ships and submarines demands effective countermeasures for defence. Detection, classification and localisation of an attacking torpedo is the first step towards launching effective countermeasures. Studies are on the rise to use the existing sonar systems to detect torpedoes and subsequently use countermeasures. The use of towed array sonar systems for torpedo detection and acoustic counter measures are the most recent and not reported much in open literature. This paper presents a modular acoustic counter measure approach using towed decoy against acoustic homing torpedoes. Describes the technologies and algorithms required for different modes of towed decoy, which is effective against both active and passive acoustic homing torpedoes. Towed decoy signal generation schemes and their realisation using digital signal processing hardware are outlined in this paper.

Keywords: Torpedo defence system; Acoustic decoys; Towed decoy; Decoy signal generation; Towed array Sonar

1. INTRODUCTION

The 'Torpedo' remains as one of the oldest and deadliest weapon in naval warfare against both surface and submarine targets[1]. The older torpedoes use gyroscopic guidance for either straight running or pattern running. However, the modern torpedoes rely on acoustics for homing and attacking a target. Torpedoes work either in passive, active or mixed homing modes. In the passive homing mode, the torpedo will be searching for sources of acoustic signatures. In active homing mode, torpedo will be transmitting acoustic pulses and will be looking for its echoes from nearby targets. In the mixed mode, torpedo will switch between active and passive modes to maximise detection probability.

Torpedo defence is a major area of concern for both surface ships and submarines. The two essential functionalities of a torpedo defence system are to detect the torpedo and to help the platform to evade its attack[2]. There are two approach for the latter task: one is hard-kill and the other is soft-kill. In hard-kill, the attacking torpedo is destroyed by another torpedo, which is an anti-torpedo torpedo[3]. In soft-kill, the torpedo is lured away from the platform and controls its trajectory using decoys till its battery-life gets exhausted. The soft-kill method is generally executed in different steps[4]. Detection and tracking of targets within the detection range is the first step is torpedo defence. Classification of torpedo targets and Identification of the torpedo threat parameter are the next step. Performing escape manoeuvre and tactical deployment of available countermeasures are the final steps in torpedo defence. Towed decoy (TD) comes first in the list of countermeasures for torpedo defence. This paper describes the technologies and algorithms required for different modes of towed decoy and how that can be effectively utilised against passive, active and mixed homing torpedoes.

Received : 17 July 2018, Revised : 16 April 2019
Accepted : 10 May 2019, Online published : 16 December 2019

2. ROLE OF TOWED DECOY IN TORPEDO DEFENCE

The distinct elements of a torpedo defence system are sonar sensors, highly automated torpedo data processing system and towed and expendable decoys (ED)[5]. A typical configuration comprises of hull mounted sonar and towed array sonar for torpedo detection is passive mode, TD and ED for torpedo decoying are as shown in Fig. 1.

Towed decoy is a part of receiver array (RA). Receiver array is a linear array of acoustic sensors used for the detection of torpedo targets. Receiver array can be operated at desired depth by controlling the payout length of the tow cable or by adjusting the speed of the towing platform. Receiver array is operated in the low frequency region of the acoustic spectrum for long range detection of torpedoes in passive mode. Hull mounted array (HMA) is also used for the detection of torpedoes. The HMA operates at relatively higher frequency

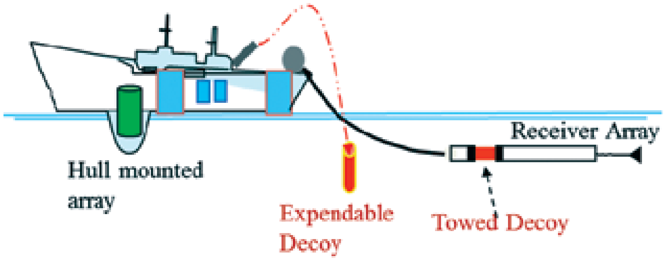

Figure 1. Configuration of torpedo defence system.

band compared to RA. The HMA provides good detection of the targets in the surface layer. The RA and HMA together provide panoramic detection of torpedoes which operates at different depths.

Once a torpedo is detected and classified using RA and HMA, the operator enables acoustic decoys for escaping the attack. Acoustic decoying is the process of fooling the torpedo homing system by introducing additional false targets in the form of TDs and ED[6,7]. In this role, the decoys either individually or in combination seduce, confuse and eventually decoy the incoming torpedo attack. Decoys generally operate in the same frequency band as that of the homing frequency band of torpedoes. The modes of operations of both the decoys are similar. The TD is generally part of the wet end sensor system and hence integral with the ship. The TD is capable of reactive mode of operation and gets activated either automatically or through operator switching. It can be streamed at any depth and also operated for required duration since it is powered from the towing ship. Expendable decoys are stand alone systems launched away from the ship. The ED is battery powered and hence has a finite life[8,9].

The strategy employed by ship for decoying a torpedo attack from aft sector and ahead sector are different. The direction of arrival of the torpedo is identified by processing the acoustic signals received through RA and HMA. Depending upon the direction of arrival of the torpedo, the countermeasure strategy will be finalised. For a torpedo launched at intercept course from the firing platform to attack the ship from aft sector, the torpedo will be seduced by the towed decoy as soon as it enters into the zone of influence of towed decoy. Torpedo deviates from its original trajectory and it can be controlled using TDs and EDs till its battery life get exhausted.

For a torpedo which is fired from ahead sector, towed decoy is switched on and ship alters its course immediately after detecting torpedo attack. Alteration of ship course will ensure that the towed decoy is getting exposed to torpedo. When the torpedo enters into the zone of influence of towed decoy , torpedo trajectory can be controlled initially using TD and then subsequently using EDs.

3. TOWED DECOY CONFIGURATION

A typical functional block diagram for assembly of towed decoy is as shown in Fig. 2. The TD is constructed as a flexible array module which contains wideband acoustic projector (P), intercept sensor (IS), power amplifier and electro mechanical connectors (C1 and C2) on both ends. Towed decoy is interfaced with other towed arrays sonar modules using electro-mechanical connectors. Towed decoy works with the help of a decoy signal generation module and also intercept signal analyser module. The decoy signal generator generates signals required for different modes of operation. The intercept sensor output is analysed and the details of the detected pulses are fed to the decoy signal generation module. These inputs will be used for multi-mode operation like echo repeater mode.

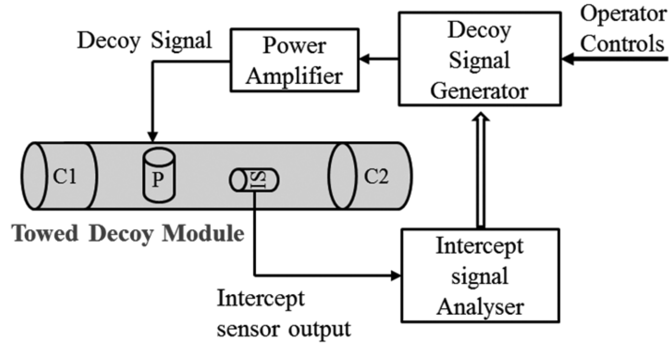

Figure 2. TD functional block diagram.

4. TOWED DECOY MODE SELECTION LOGIC

Towed decoy is capable of operating in multiple modes namely jammer mode, echo repeater mode, mixed mode and synthetic mode. Different modes are effective against torpedoes with specific homing modes.

Jammer mode: This mode is for confusing a passive homing torpedo. The TD transmits broad band ship like signature at a source level greater than that of the own ship.

Echo Repeater mode: This mode is used against an active homing torpedo. The active transmission from the torpedo, after interception and processing is re-transmitted to imitate the actual echo coming from the ship, but at a higher source level.

Mixed mode: This mode uses combination of jammer mode and echo repeater mode. This mode is used against torpedoes with mixed homing mode.

Synthetic mode: This mode is used against an active torpedo whose transmission parameters are known in advance. In this mode, active echoes are synthetically generated and transmitted to meet the transmission parameters of the torpedo. This mode is generally used as a backup mode or as a test mode.

The mode in which the TD operates is decided either automatically using the inputs received through sensors based on a pre-programmed logic, or manually through operator intervention.

5. TOWED DECOY SIGNAL GENERATION

Decoy signal generation for different modes of operation is as explained as follows:

5.1 Jammer Mode

The jammer mode involves generation of either a pre-defined spectrum like the ship's signature, or any arbitrary spectrum specified online by the user. Signal generation scheme for Jammer mode is as shown in Fig. 3.

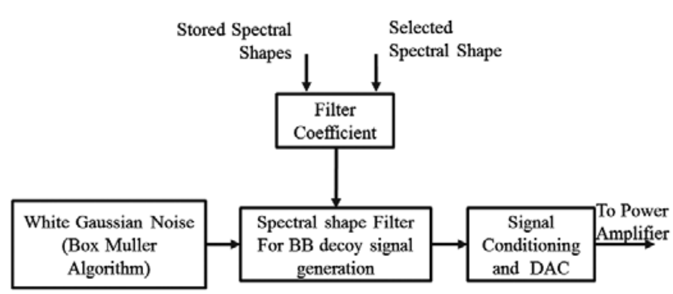

Figure 3. Signal generation scheme for jammer mode.

The selection control for the signal generation can be done either by the user or automatically by the system, as part of the decoying tactics. The steps involved are given below

Stored spectral signature: Gaussian white noise is generated using linear congruential method followed by Box-Muller algorithm[10,11]. In linear congruential method, a random number $x(n)$ is generated from the preceding random number $x(n-1)$ by the rule

$$x(n) = (Ax(n-1) + C)\,\text{modulo}\,p \tag{1}$$

The distribution of the random sequence thus generated is made Gaussian by the Box-Muller Algorithm. The most basic form of the Box-Muller method is

$$x_1 = \sqrt{-2\ln(u_1)}\cos(2\pi u_2) \tag{2}$$

$$x_2 = \sqrt{-2\ln(u_1)}\sin(2\pi u_2) \tag{3}$$

Here u_1 and u_2 constitute the uniformly distributed random numbers generated using the linear congruential algorithm and x_1 and x_2 are the resultant random numbers having Gaussian distribution with zero mean and standard deviation of 1. The stored impulse response corresponding to the desired spectral signature is retrieved and the generated Gaussian white noise is convolved with the same.

Online spectral generation: In this case the first step is the generation of Gaussian white noise as explained above. Next step is the design of FIR filter from user specified spectral values[12]. The user has to enter N values of magnitude, equally spaced in frequency, of the desired spectrum through the GUI. An FIR filter of the same frequency response is then designed using the least square error criterion. If $D(e^{j\omega})$ is the desired spectral response and $H(e^{j\omega})$ is the designed response, then the squared error is given as

$$E = \int \left| H(e^{j\omega}) - D(e^{j\omega}) \right|^2 d\omega \tag{4}$$

$$H(e^{j\omega}) = \sum_{n=0}^{N-1} h(n) e^{j\omega n} \tag{5}$$

where $h = \{h(0), h(1) \ldots h(N-1)\}^T$ and $e = \{1, e^{-j\omega}, \ldots, e^{-j(N-1)\omega}\}^T$

Equation (4) can be written as

$$E = h^T Q h - h^T p + r \tag{6}$$

where $Q = 2\int \text{Re}\left(e(\omega) e^H(\omega)\right) d\omega$

$$p = 2\int \text{Re}\left(D(e^{j\omega}) e^*(\omega)\right) d\omega \text{ and } r = 2\int \left| D(e^{j\omega}) \right|^2 d\omega .$$

The optimum value of h that minimizes the error term E can be obtained by taking the derivative and equating to zero. The optimum value of h is

$$h_{opt} = Q^{-1} p \tag{7}$$

5.2 Echo Repeater Mode

Whenever the intercept processor detects an active transmission from an incoming torpedo, the decoy automatically switches over to the echo repeater mode. In this mode, whatever intercept signal is received will be retransmitted after making appropriate pulse width, amplitude, time delay and doppler modifications to simulate the real characteristics of the echo of the ship at a higher source level than that of actual echo from ship.

The echo from the ship will be a function of the length and profile of the ship. Hence, the resultant signal at the torpedo end will be a sum of the echoes coming from different points of the ship surface. Here, the ship is assumed to be divided into $N+1$ regions of equal width such that each region can be assumed to be a single reflector point and only a single echo signal arises from one point at any instant of time. The time delay in the echoes from the two farthest points of the ship is given by

$$\tau = L\cos(\theta)/c \tag{8}$$

where L is the length of the ship, θ is the bearing of the torpedo w.r.t ship's head and c is the speed of sound.

The time delay between the echoes from two adjacent regions will be $1/N^{th}$ of τ which will corresponds to M samples. Hence the output signal can be expressed as

$$y[n] = k_0 x[n] + k_1 x[n-M] + \ldots\ldots.. + k_8 x[n-M] \tag{9}$$

where k_0, k_1, ···, k_8 are the attenuation coefficients.

A valid assumption would be that the ship has a uniform structure throughout its length underwater. Hence the attenuation suffered on reflection from all the regions will be the same *i.e.*

$$k_0 = k_1 = k_2 = \ldots\ldots = k_8 = k$$

Signal generation scheme for Echo repeater mode is shown in Fig. 4.

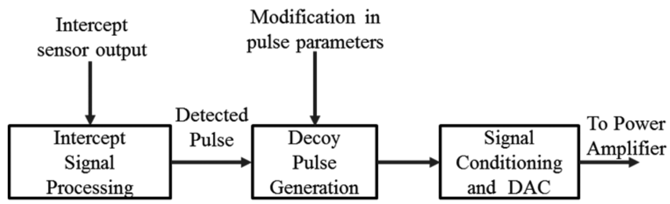

Figure 4. Signal generation scheme for echo repeater mode.

5.3 Mixed Mode

When a decoy is to be operated against a torpedo, whose homing mode is unknown, TD in mixed mode is suggested. In this mode, initially, decoy will be operated in jammer mode for T_1 s. After T_1 s, it will listen for active transmissions from torpedo for next T_2 s. If any valid active transmissions are received within this T_2 s, decoy will switch over to echo repeater mode, else continue for T_1 s in Jammer mode and T_2 s in listen cycle. If there are no pulses received for T_3 s in echo repeater mode, decoy will switch over to T_1 and T_2 switching cycle. Signal generation scheme for Mixed mode is as given in Fig. 5.

5.4 Synthetic Mode

This mode is selected when the decoy is required to transmit active pulses as per the transmission parameters of a known torpedo. Different waveforms like pulsed continuous (CW) or linear frequency modulation (LFM) specified by the operator need to be generated in this mode as per the scheme shown in Fig. 6. Pulsed continuous waveform is a type of pulse with fixed frequency for a selected pulse width (PW). The pulse will be repeated after selected pulse repetition interval

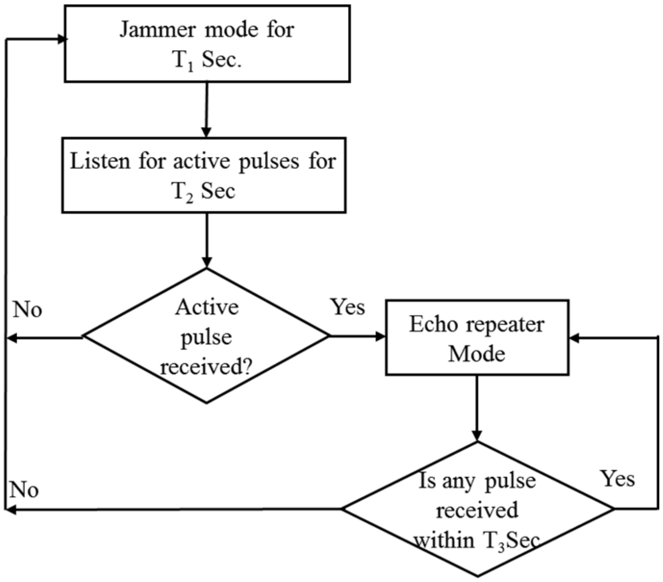

Figure 5. Signal generation scheme for mixed mode.

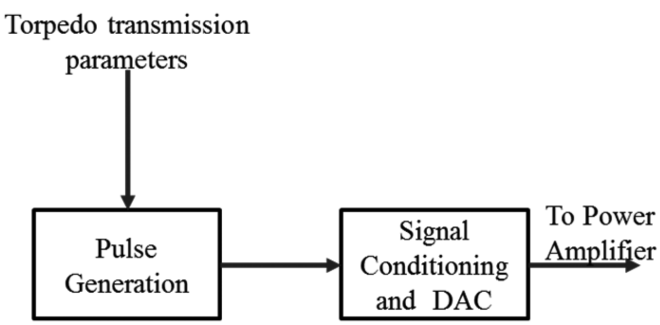

Figure 6. Signal generation scheme for synthetic mode.

(PRI). The parameter inputs for CW will be frequency, PW, PRI and signal strength. The parameter inputs for LFM are the start and stop frequencies, PW, PRI and signal strength. The CW and LFM generation has been implemented using the digital frequency synthesis (DFS) method[13]. This method uses a phase accumulator, which accumulates the phase increments. The phase increment is computed as

$$\Delta\phi = F_0 2^N / F_s, \quad (10)$$

where F_0 is the desired frequency of the sine wave and F_s is the sampling frequency, N is the binary width of the phase accumulator. The size of the phase increment determines the frequency of the output while the binary width of the phase accumulator determines the minimum frequency that can be generated. The frequency resolution is given by

$$\Delta F = \Delta\phi F_s / 2^N \quad (11)$$

A look-up table is used for phase-to-sinusoid amplitude conversion. Since the size of the look-up table increases exponentially with increase in N, it is not feasible to use a look-up table of size 2^N. Hence, the phase accumulator has to be truncated and only p Most Significant Bits (MSBs) are used. To generate the LFM sinusoid signal, an additional phase increment, known frequency modulated as the LFM phase increment is computed.

$$\Delta\phi_{LFM} = [(F_1 - F_2)/PW]2^N / F_s, \quad (12)$$

where F_1 is the start frequency, F_2 the stop frequency and PW is the pulse width. The LFM phase increment is then added to the phase increment $\Delta\phi$, to get the total phase increment $\Delta\phi_{tot}$. This total phase increment is then accumulated in the phase accumulator to get the LFM signal.

6. HARDWARE IMPLEMENTATION

The hardware implementation scheme of towed decoy signal generation system is shown in Fig. 7.

The system is realised using two SHARC-ADSP20162 based digital signal processor (DSP) boards, one PowerPC-7410 based display data processor (DDP) board and one decoy signal conditioner card. The decoy signal generation and mode selection logic is implemented in first SHARC DSP board[14,15]. The intercept pulse detection, information extraction and A/D conversion of decoy signal are done in the second DSP board. The interface between the GUI and the decoy system is implemented in DDP. The interface for the decoy signal generator board with the analog card is through link port of the SHARC processor. The digital data is transmitted to the analog card over the data lines of the link port at the processor clock speed. The MSB of each nibble is used as a sync bit. This digital data is converted to analog and send to the decoy sensor after power amplification stage. The DDP and the DSP board communicate over VME back plane.

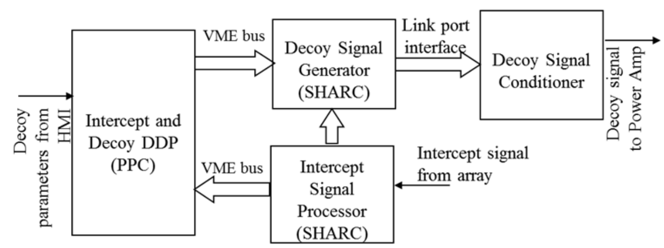

Figure 7. Hardware realisation of decoy signal generation System.

7. RESULTS

Multi-mode towed decoy, which is effective against both active and passive acoustic homing torpedoes have been successfully developed and tested. Towed Decoy was tested against both passive and active homing torpedoes during sea trials. Performance of TD against a passive homing torpedo is captured in the bearing time record (BTR) of towed receiver array sonar display is shown in Fig. 8. In BTR display, x-axis represents the bearing and y-axis represents time history. BTR shows relative bearing of the targets with respect to towed array. 90^0 correspond to broad side, 0^0 correspond to ship's direction and 180^0 correspond to aft. The current time is marked on top of the display and the history is on the bottom. Target energy is marked as green intensity levels on the display. The torpedo trajectory is marked in green traces in the BTR. Initially, the torpedo was chasing the ship, till the TD was switched ON. The deviation in the torpedo trajectory which is observed in the BTR, is due to the influence of TD. When TD was switched ON, the torpedo was seduced by the TD and it was homed on to it. Deviation in the torpedo trajectory post TD switched ON is evident in the Fig. 9.

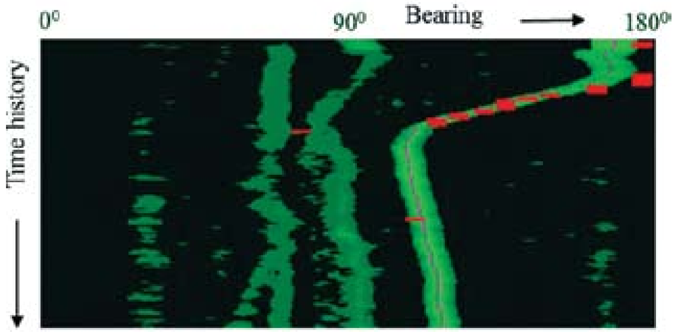

Figure 8. Towed decoy seducing passive homing torpedo.

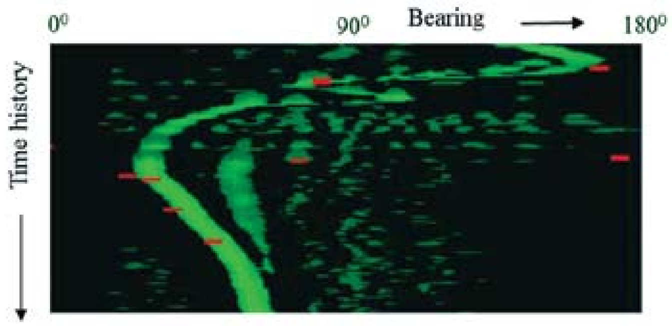

Figure 9. Towed decoy seducing active homing torpedo.

Performance of TD against an active homing torpedo is shown in the Fig. 9. When the TD was switched ON, torpedo gets deviated from its course and gets homed on to the TD. Deviation in the torpedo trajectory post TD switched ON is evident is the figure.

8. CONCLUSIONS

Towed decoy operation and effectiveness of decoy mode selection logic is tested and verified during multiple sea trials using different types of torpedoes. Provision for changing doppler to mimic speeds other than actual ship speed and provision for range gate delay in echo repeater mode was also realised and tested. Adaptive noise cancellation techniques for more efficient operation of towed decoy systems are the area for future research.

REFERENCES

1. Ramanarasaiah, N.K. Introduction to torpedo technology, DRDO Monogram Series-I, 1997.
2. AjithKumar, K.; Jomon G. & Jagathyraj, V.P. Requirements analysis of an integrated sonar suite for surface ships: Systems engineering perspective. *Def. Sci. J.*, 2014, **64**(4), 366-370.
   doi: 10.14429/dsj.64.4486.
3. Zhang, R.; Yuan, Z.; Ye, L.; Liu, Z. & Zhang, C. Analysis of maneuver occupying angle of submarine launching anti-torpedo torpedo. *In* Chinese Control and Decision Conference (CCDC*)*, 2018, pp. 4002-4007.
   doi: 10.1109/CCDC.2018.8407818.
4. Chen, Y. & Qiu, Y. Simulation-based effectiveness analysis of acoustic countermeasure for ship formation. *In* 4th International Conference on Systems and Informatics (ICSAI)*,* Hangzhou, 2017, 756-761.
   doi:10.1109/ICSAI.2017.8248387.
5. Chen, Y.C. & Guo, Y.H. Optimal Combination Strategy for Two Swim-Out Acoustic Decoys to Countermeasure Acoustic Homing Torpedo. *In* 4th International Conference on Information Science and Control Engineering (ICISCE)*,* 2017, pp. 1061-1065.
   doi: 10.1109/ICISCE.2017.222.
6. RaviKumar, E. & Rao, K. S. Anti-Submarine /Ship Warfare (ASW): Tactical Assessment and Statistical System Analysis. *In* International Conference on Systemises, Cybernetics and Informatics, 2009, CS-2.1, 31–36.
7. Akhil, K.R.; Ghose, D. & Rao, K.S. Optimizing Deployment of Multiple Decoys to enhance ship survivability. *In* Proceedings of 26th American Control Conference conducted by American Automatic Control Council, New York, USA, 2008, pp. 1812–1817.
   doi: 10.1109/ACC.2008.4586755.
8. Kyung-Min, S.; Song, H. S., Kwon, S.J. & Kim, T. G. Measurement of effectiveness for an anti-torpedo combat system using a discrete event systems specification-based underwater warfare simulator. *J. Def. Model. Simulation: Appl., Methodol., Technol., 2011,* **8**(3), 157–171.
   doi: 10.1177/1548512910390245.
9. Lautour, N.J. & Trevorrow, M. Initial study on expendable acoustic countermeasures for torpedo defence. *DTA Report* 341, 2012.
10. Knuth, D.E. The art of computer programming, Addison–Wesley, 1997, **2**(3), 17–19.
11. Box, G. E. & Muller, M.E. A note on the generation of random normal deviates. *Annals Math. Stat.*, 1958, **29**(2), 610–611.
    doi: 10.1214/aoms/1177706645.
12. Tseng, C.C.; Pei, S.C. & Hsia, S.C. Computation of fractional derivatives using Fourier transform and digital FIR differentiator. *Signal Processing*, 2000, **80**, 151–159.
    doi: 10.1016/S0165-1684(99)00118-8.
13. Tierney, J.; Rader, C.M. & Gold, B. A digital frequency synthesizer. *IEEE Trans. Audio Electro Acoustics*, 1971, **19**(1), 48–56.
    doi: 10.1109/TAU.1971.1162151.
14. ADSP 2106X Reference Manual, Analog Devices, 2013.
15. MPC7410/MPC7400 RISC Microprocessor Reference Manual, Rev. 2, Free scale Semiconductor, Oct 2008.

CONTRIBUTORS

Mr Jomon George received his BTech (Electrical and Electronics Engineering) from Mahatma Gandhi University, Kerala and MTech (Electronics) from Cochin University. Currently pursuing his PhD at Cochin University. He is working as Scientist 'G' at DRDO-Naval Physical and Oceanographic Laboratory, Kochi. His research interests include: Sonar system design, Sonar signal processing and Towed array sonar systems.

In the current study, he has carried out the basic research, system implementation, data analysis and writing original manuscript.

Ms P. Sinchu received her BTech (Electronics and Communication Engineering) from NIT, Calicut and ME (Signal Processing) from IISc, Bangalore. She is working as Scientist 'E' at the DRDO-Naval Physical and Oceanographic Laboratory, Kochi. Her research interests include sonar signal processing, active sonar reverberation studies and Sonar target tracking algorithms.
In the current study, she helped in system realisation, data processing and preparation of figures.

Dr K. Ajith Kumar received his BTech (Mechanical Engineering) from University of Kerala, MTech (Engineering Mechanics) from IIT, Madras and PhD from Anna University, Chennai. He is working as Scientist 'G' at DRDO-Naval Physical and Oceanographic Laboratory, Kochi. His research interests include: Application of systems engineering in design of major systems, sonar systems design, design of engineering systems for underwater applications and project management.
In the current study, he helped in planning and execution and critically reviewing the manuscript.

Dr T. Santhanakrishnan received the MSc (Physics) from Madurai Kamaraj University, Madurai, India, MTech (Lasers and Electro-Optical Engineering) and PhD in applied optics from Anna University, Chennai. He is working as Scientist-F at DRDO-Naval Physical and Oceanographic Laboratory, Kochi. His research interests include: Development of optoelectronic systems for under water applications, optical interferometry, fiber optic hydrophones, laser-based instrumentation, Big data analysis, sentiment analysis from tweets, polymer composites, underwater target detection and tracking, and thin film PZT sensors.
In the current study, he helped in formulation of concept and research objectives, overseeing the research activity and critically reviewing the manuscript.