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Analysis of a SONAR Detecting System Using Multi-Beamforming Algorithm

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ABSTRACT

Sonar (Sound Navigation and Ranging) system is an advanced underwater object-detecting system for navigation. The sonar system aids in detecting obstacles and the presence of enemies within a given range. The sonar system detects the targeted objects by identifying the radius and range of the targeted objects. One of the major problems that affect the application of the sonar system is the inability to detect objects due to excessive echoes and noise in the spectrum. The excessive echoes created reverberations that tend to distort the original reflected signal of the sonar system. This research aims to develop a sonar system that can detect a target object at 15km using a beamforming technique. The technique aids in creating a very high-level concentration on the objects by sending multiples of the same signals to one receiver, thereby reducing reverberation and transmission losses. The results show that 15 obstacles were detected at 15km, and reverberations were reduced by 2dB, thereby improving the visibility of the detected signal within its range with the lowest transmission loss of 0.5dB compared to the ultrasonic sonar system and the conventional echo object detecting system having a transmission loss of 3.12dB and 5.67dB respectively.

Keywords **-Beamforming, Sonar, Echo, Underwater, Transmission loss**

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I. INTRODUCTION

Modern sonar systems are typically built using a hydrophone array to enhance the capacity to locate and identify underwater targets. Beamforming is a technical term used to describe how the sonar system uses the relative delay of the array signal for in-phase superposition to locate the target. The area of underwater acoustic engineering is currently focusing on the development of high-speed real-time active sonar systems with multi-beams as the primary technology [1]. The hydrophone array's aperture is the primary determinant of angular resolution in multi-beam sonar systems. However, this increases the aperture of the array to avoid the grating lobe effect, i.e., the hardware needs to provide more signal acquisition channels, but it is noteworthy that the volume of the hardware system and its internal signal processing unit are typically limited. Narrowing the main lobe width of the natural beam angle leads to an increase in the angular resolution of the positioning [1]. As a result, increasing the aperture increases both the workload on the hardware system and the number of calculations that the signal processor must perform. The system cannot thus deliver the needed real-time positioning. The time needed for processing each frame of the echo signal in the multi-beam sonar system is also decreased in order to increase range resolution. This phenomenon increases the amount of input data received per unit of time and raises the demands on the signal processor's throughput. Consequently, it is challenging to realize high-speed real-time positioning and high-resolution positioning with restricted hardware resources. Multi-beam sonar systems must operate well in real-time as underwater acoustic engineering advances. Designing a multi-beam sonar system with excellent computational performance that may be employed in underwater acoustic engineering applications is therefore extremely important and valuable [1].

Review of Related Work

[2] provides an overview of the integrated sonar suite and introduces techniques for gathering user needs using systems engineering principles. Preliminary system configuration is developed based on operational, functional, and physical requirements following requirements investigation and analysis of the ISS. The prototype system's development quality is enhanced by this method using the concepts of systems engineering. Additionally, Concept of Operations (CONOPS) discussions serve as the foundation for the evaluation and validation of the prototype system.

[3] stated that SONAR systems, either passive or active systems, and underwater wireless networks as an emerging area in the field are employed for underwater signal processing, Hidden Markov Model (HMM)-based method has been researched, and simulation results and examples have been published. Even with low SNR, which is typical

of most SONAR systems, the capacity of HMM to represent various kinds of underwater noises is noteworthy. They investigated the Hausdorff Similarity Metric (HSM), a novel measure for differentiating between class traits. When spectral components are employed as features, HSM performs better in low SNR situations than the other one-dimension measures, such as Minkovsky-based measures.

[4] designed and created a sonar-based obstacle detector and expressed the need for intelligent automotive systems that can detect and avoid collisions, which has been a significant challenge for the automotive industry and for which extensive research is ongoing to offer solutions. SONAR-based obstacle detection and avoidance system detects obstructions in its path, determines their distance, and then warns the controller of the obstruction by voice prompt and LCD display. The technology can identify impediments up to 300 centimetres away.

[5] suggest a layered simulation architecture for functional testing that distinguishes between intra-subsystem behaviours and inter-subsystem communications. Three different simulator kinds were created and made modular. The relevant physical simulators receive simulated data from the CM simulator, which simulates actual combat situations. Each physical simulator realizes its dynamics and behaviours using the simulated data by mimicking the console panels of the respective system. By isolating the domain processing required to create the system view from the processing, the proposal improves the automation's transparency for the designer and the user. For simulation testing, the created software enables parallel management of the internal interfaces between combat system subsystems and external interfaces to the combat system. They concluded that models allow for simulation and analysis, which can help identify design flaws more quickly than prototyping.

Basic Approach of SONAR

Active and passive systems are the two main groups. Figure 1(a) shows a passive SONAR device for monitoring the underwater environment without using energy to penetrate the water. On the other hand, an active SONAR system can function similarly to a RADAR by exploiting the results of signals that are directed at targets. Even in highly noisy situations, underwater signals received from passive SONAR include useful hints for source identification. Early SONAR system development efforts at acoustic signal recognition and categorization based on spectral features were not particularly successful [6]. Additionally, locating the classification standards for objects underwater is more challenging than for surface vehicles. For choosing the discriminating features and the classification algorithms, it is crucial to comprehend the nature and characteristics of both ambient noise and the acoustically transmitted noise of boats. The ambient noise main sources are biological organisms' activities, oceanic turbulence, seismic disturbances, distant shipping, wind, and thermal noise [6]

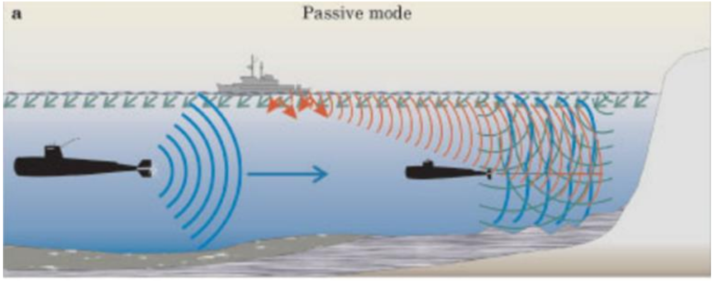

Figure 1(a): Passive Sonar [3]

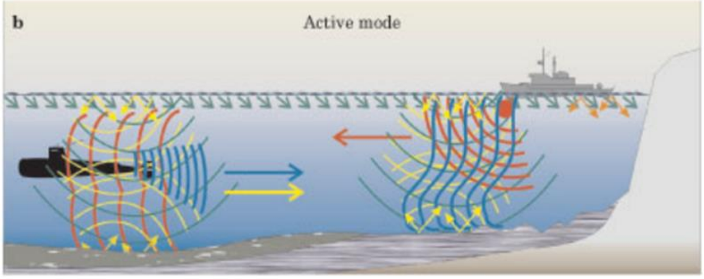

Figure 1(b): Active Sonar [3]

There are both broadband and narrowband components to the acoustic radiation noise that the ship's machinery and motion in the water produce. In general, the spectrum of acoustic radiation noise changes as speed does [7].

Other authors have made significant improvements in the sonar systems, however, there are limitations such as single beam sonar signal. Using the multi-beamforming sonar system will improve the sonar system for better response and authenticity of the detected objects, the intense multi-beamforming will create an intense concentration of the signal towards the sonar receiver reducing the reverberated echoes and transmission losses.

II. MATERIALS AND METHOD

The method used in this research work is known as the multi-beamforming method. The multi-beamforming is a digital technique that forces the sonar to focus the transmitter and receiver in a particular direction. The side-to-side direction focus of the sonar system is known as the azimuth and the up-to-down focus direction is known as the elevation. The multi-beamforming can be used to focus the sonar system over both azimuth and elevation direction with a very high concentration which results in the reduction of losses due to reverberations.

Determining the Active Sonar System Signal

A sonar system must be designed with a variety of considerations in mind. The fundamental formula for an active sonar is given in the noise-limited scenario [3]

$$SL - 2TL + TS = NL - DI\ DT \quad (1)$$

Where SL is Source level in dB, TL is Transmission loss (dB), TS is Target strength (dB), NL is Noise level (dB), DI is Directivity index (dB), DT is Detection threshold (dB)

In the equation (1) above, the echo level is on the left, and the noise masking level is on the right. Given below is the analogous equation for the reverberation-limited situation.

$$SL - 2TL + TS = RL + DL \quad (2)$$

Where RL is the Reverberation level (dB)

The reverberation masking level is supplied as the right-hand side of the equation above.

It should be emphasized that the designer has considerable control over variables like SL and DI. DT and TL are at least indirectly controllable. NL & d TS are out of the designer's control; they only depend on the platform and the target, respectively.

The formula yields the source level (SL).

SL=171.6+10logP + DI (3)

where 171.6 dB means 1 watt of acoustic power produces 171.6 dB at 1 Yard from a point source and P is the acoustic power radiated by the transducer in watts.

It is seen from the sonar equation that SL is directly proportional to the echo level and hence the detection range. Also, the source level is directly proportional to power P and the Directivity index during transmission.

Estimate the largest array dimension (that is, the Radius (R) and the height (H) that the platform can support. On such an array, the active area A is provided by [8]:

$$A = 2\pi RHa \quad (4)$$

Where a = the ratio of the active area to the total area of the curved surface of the array, H is the height of the active area, R is the Radius of the active area

At any frequency F corresponding to a wavelength in water, the vertical beam width is given approximately by

$$\theta_v = \frac{\lambda}{H} Radians \quad (5)$$

Where θ_v is the vertical beam width, H is the height of the active area, λ is the wavelength.

The typical cavitation threshold is 113 watts/cm2. For pulsed transmissions, it is typical to use up to 112 watts per centimetre. Consequently, by applying equation (6), the power that the array may radiate is given by [3]

$$P = \frac{A}{2} = \frac{2\pi RHa}{2} = RHa \quad (6)$$

Where H is the height of the active area, R is the Radius of the active area, A is the active area.

For arrays operating at a depth of h meters, the power that can be radiated is given by.

$$p = \pi RHa(1 + \frac{h}{10}) \quad (7)$$

Where h is the depth of the water in meters

The corresponding electrical power of the signal required to stimulate the signal is [9]:

$$p = \pi RHa(1 + \frac{h}{10})/\eta \quad (8)$$

where η is the efficiency

Substituting equation (7) in equation (3) we get the source level in the Omni-mode of transmission as [8]:

$$SL(omni) = 171.6 + 10logRHa + 10\log\left(1 + \frac{h}{10}\right) + DIv \quad (9)$$

where DIv is the directivity index (vertical)

The power that is radiated by each aperture is given by [9]:

$$p = \frac{\pi RHa\left(1+\frac{h}{10}\right)}{Nx} \quad (10)$$

The aperture angle is given by:

$$\theta_{N\infty} = 2\pi/Nx \quad (11)$$

The corresponding aperture width is [5]:

$$A_{N\infty} = 2Rsin(\frac{\pi}{Nx}) \quad (12)$$

The transmission directivity DI is given by [8]:

$$DI = 10\log\left(\frac{4\pi}{\theta_v} \times \theta_H\right) \quad (13)$$

where θ_V is the vertical beam width given by equation (14) and θ_H is the horizontal beam width given by [5]:

$$\theta_H = \frac{\lambda}{2R}\sin\left(\frac{\pi}{Nx}\right) \quad (14)$$

substituting these values in equation (15) we get

$$DI = 10\log\{\left(\frac{4\pi}{\lambda^2}\right)2RH\sin\left(\frac{\pi}{Nx}\right)\} \quad (15)$$

therefore, the source level in RDT is given by

$$SL(RDT) = 171.6 + 10log\left\{\left(\pi RH.\frac{a}{Nx}\right)\left(1 + \frac{h}{10}\right)\right\} + 10\log\{\left(\frac{4\pi}{\lambda^2}\right)2RHsin\left(\frac{\pi}{Nx}\right)\} \quad (16)$$

Beamforming

The process is fundamentally the same in both domains: signals are sampled over an array, phased (i.e., delayed) to move the array in a specific direction, and then the phased signals are added. It takes some geometry to convert the guided "look" direction to the proper amount of delay at each node to phase the incoming signals. According to [2] and [9], this delay is linearly proportional to Dx. The wavefront would be received by adjacent nodes at a difference in time of:.

$$\delta = \frac{\Delta x}{c} = \frac{dsin(\theta)}{c} \quad (17)$$

where d = the distance between adjacent nodes, h = steering angle from the arrays perpendicular, c = Speed of sound in water

Individual node, shown by their node number m, will get a signal at angle h at a relative delay of:

$$(m = 1)\delta \quad (18)$$

Reference node zero, In the frequency domain, it is possible to construct a vector s that, when multiplied by the relevant incoming signals, will correctly phase the system [3]. This vector is designed as:

$$s = [1, e^{-jkdsin(\theta)}, e^{-2jkdsin(\theta)}, e^{-3jkdsin(\theta)}, e^{-4jkdsin(\theta)}, e^{-5jkdsin(\theta)}, , e^{-j(M-1)kdsin(\theta)} \quad (19)$$

where

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c} \quad (20)$$

is equal to the wave number and M is the number of nodes. The final beamforming equation is a summation, x(t), of the phased signals multiplied by a windowing weight matrix w(t)

$$y(t) = \underline{W}^t\underline{x}(t) \quad (21)$$

Or

$$y(\omega) = W^{\omega}\underline{x}(\omega) \quad (22)$$

Reverberation

The scattering strength, often known as the fundamental ratio on which the reverberation depends, is given by [9]:

$$S_s = 10\log\left[\frac{i(scat)}{i(inc)}\right] \quad (23)$$

Where i (scat) = intensity scattered by unit area or volume, i(inc) = intensity of incident plane wave.

The design of the beamforming algorithms is shown on the screenshot of the beamforming algorithm on Matlab in figure 2.

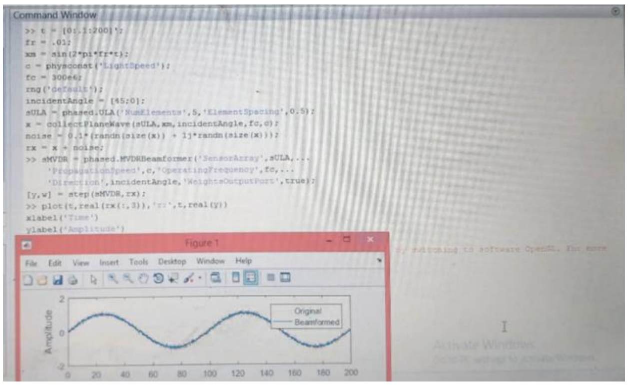

Figure 2: Screenshot of the Sonar System using the beamforming Algorithm.

III. RESULTS AND DISCUSSION

Emitted Sonar Signal

The transmitted signals of the sonar system are shown in the figure 3. As it can be shown the sonar signal radiation magnitude at 2.8dB at a 10 second resonation stretches underneath the water ways for targeted objects detections. The signal hits the targeted objects and reflect to the receiver at 10 seconds. The reflected signal is being received by the sonar transducer converting the ultrasound to an audio-visual meaning for proper interpretations.

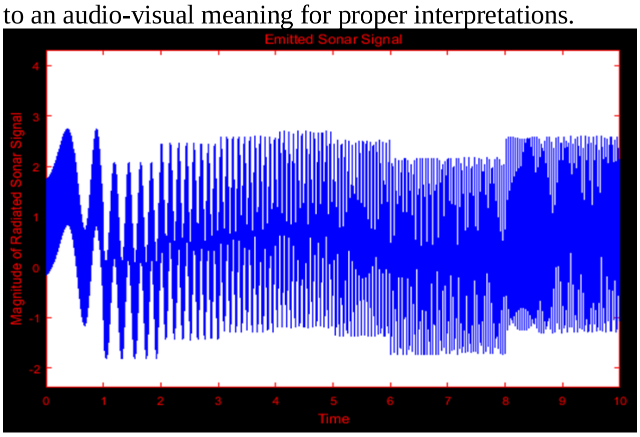

Figure 3: Emitted Sonar Signals

Beamforming of the Sonar Signal

The beam former response in figure 4 are actual beamforming signals representing the original signal of the system. The major ideology of the beam former technique is to reduce the level of reverberation and attenuation of the sonar signal. The conventional beam former aides in curbing sonar attenuations and improves the signal quality of the sonar system. Normally during transmission of the sonar signals, the signal observes some external interference, and attenuation of the signal during reflections of the sonar signal on the targeted object. However, the beam former makes the signal to be highly concentrated and improve the received signal quality, this operation is possible by transmitting multiple same frequencies at same time.

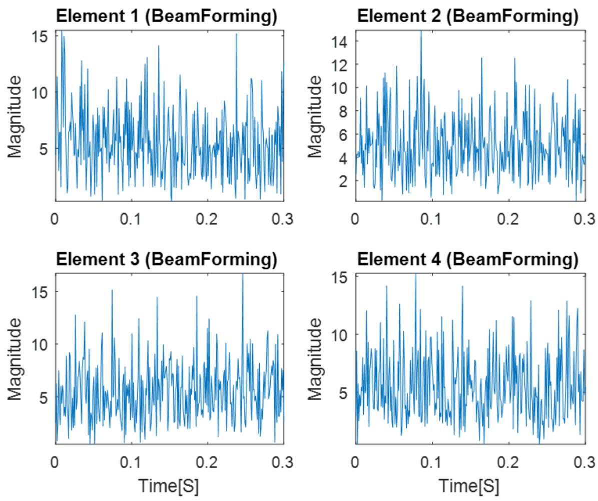

Figure 4: Beamforming sonar signals

The figure 5 as shown is the Gaussian pulse response of the sonar system signal. The sonar system underwater sends a sound signal into the water system at an ultrasonic speed. the signal hits the targeted object at an amplitude of 1 and almost 0 seconds. The speed of the sonar system is that fast to give a reflective message back to the system at microseconds.

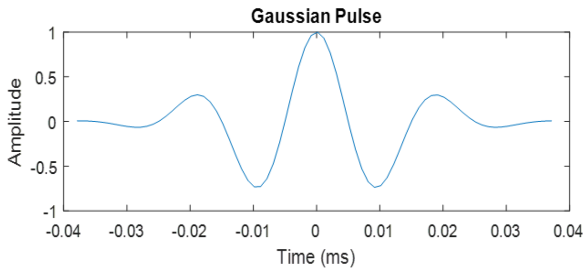

Figure 5: The Gaussian Pulse Response of the Sonar System

Received Reflected Sonar Signal

The received signal of the sonar system is shown in the figure 6. As shown in the figure the received signal at over 100KHz. The received signal is because of obstacle detection and reflective actions. The signal reflected signifies those obstacles has been detected. The point is, once an obstacle is sensed it means a possible reflection has taken place but once an obstacle is not sensed the reflective representation is zero. The received underwater sonar signal in the figure 6 represents a detected obstacle within the range of the sonar system.

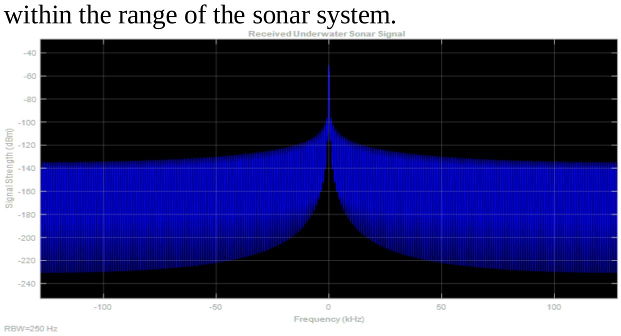

Figure 6 Received reflected sonar signal.

Reverberated Sonar Signal

Reverberated signals are mostly external representations of echoes in the sonar system which has a highly negative impact on the sonar system, thereby making it difficult for the system to interpret the actual detected targeted objects. Sometimes these reverberated signals are accompanied with noise and which results to distortions of the signals of the targeted objects. However, the result in the figure 7 shows a reduced reverberated signal in the received channel due to the beamforming technique used in this research work. The beam forming produces a multiple transmission sonar signal thereby suppressing the reverberated signal presence in the signal. It is shown that the reverberated signal has been reduced to 2dB thereby improving the visibility of the detected signals within the range of the sonar system.

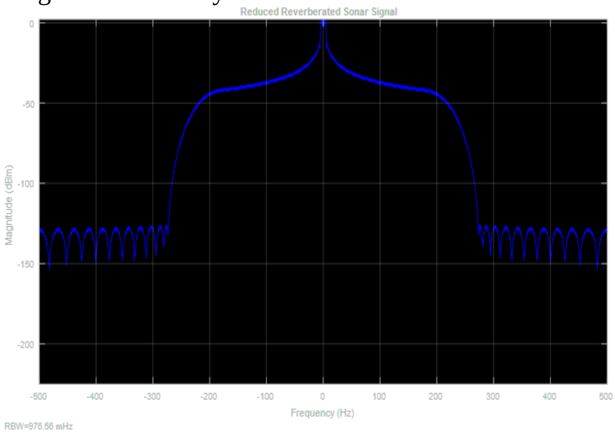

Figure 7: Reduced Reverberated Sonar Signal

Transmission Loss and Reverberated Signal

From table 1, the transmission loss of the sonar system is given at different type of sonar system. The result shows the sonar system with beamforming method has the lowest transmission loss and the echo object detector has the highest transmission loss. While the reverberation case, the beamforming sonar technique has a reduction of 2dB. Table 1 below shows the comparative result of transmission loss and reverberated signal.

Table 1: Result of Transmission Loss and Reverberated Signal

Sonar System Types	**Transmission Loss (dB)**	**Reverberation (dB)**
Beamforming Sonar System	0.5	2
Ultrasonic Sonar system	3.12	8
Conventional echo object detecting system	5.67	13

IV. CONCLUSION AND RECOMMENDATIONS

Conclusion

The research work considered the beamforming technique to improve concentration of the sonar signal on the targeted objects thereby reducing attenuations and signal interferences. The sonar system is functional up to a range of 15km with transmission losses reduced to about 2dB when beamforming technique is used. This work also considered the reverberation strength of the signal as well as the azimuth and gaussian angles.

In summary, the following contributions can be derived from this research:

i. Detection of obstacles from longer range
ii. Reverberation Reduction to 2dB
iii. Low transmission losses 0.5dB due to the beamforming technique.

Recommendations

Further research can be carried out on the possible noise and distortion of the sonar signal at the receiver due to interferences. Also, researchers can study other methods to further improve the maximum range, reduce reverberation as well as improve transmission losses.

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Biographies and Photographs

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