A PROJECT REPORT

ON

Dynamic Simulation of Directional Underwater Sonar Beamforming with Acoustic Pressure Modelling

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Signature

(K.Sudarsan)

Table of Contents

ABSTRACT

This project presents a dynamic simulation framework for visualizing directional sonar beamforming and acoustic pressure modeling in underwater environments. The system models the interaction between a mobile surface vessel and a stationary underwater transponder, using real-time animation to represent sonar beam propagation, directionality, and signal behavior.

The simulation integrates a sinusoidal acoustic signal model of the form

$\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$, where the amplitude $A(\alpha)$ is a function of the beam angle. This allows for realistic representation of direction-dependent acoustic pressure variations. The beam is dynamically formed based on the boat's position and orientation, with visual cues indicating beam angle, transmission path, and pressure levels.

The project is implemented using Python and Matplotlib, and includes interactivity through pause/play and reset controls. The results demonstrate the effectiveness of using computational modeling and animation to understand sonar behavior and acoustic propagation characteristics in marine scenarios.

This simulation provides a useful educational and research tool for exploring underwater acoustic systems, beam directivity, and real-time sonar dynamics.

Chapter 1. INTRODUCTION

1.1 Overview

Sonar systems are essential for underwater communication, navigation, and object detection. Beamforming, the process of directing acoustic energy, is a key technique used in these systems.
This project simulates the directional behavior of sonar beams between a fixed underwater transponder and a moving surface vessel. Using Python-based animation, it visually demonstrates beam propagation, angle variation, and pressure modeling in real time.

1.2 Scope and Objectives

Scope:

The primary scope of this project is to develop a dynamic and visually intuitive simulation of directional sonar beamforming and acoustic pressure modeling in underwater scenarios. The simulation aims to represent how sonar beams propagate from a transponder to a moving boat, and how acoustic pressure varies based on beam direction.

Objectives:

- To simulate the motion of a surface vessel across a horizontal axis in an underwater environment.
- To model and animate the propagation of sonar beams from a fixed underwater transponder to the moving boat.
- To implement an acoustic pressure signal model based on the equation $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$, where $A(\alpha)$ varies with beam direction.
- To visualize beam angle (θ), directional angle (α), frequency, amplitude, and pressure in real time.
- To provide interactive controls for pausing, resuming, and restarting the simulation loop.
- To offer an educational and research-oriented tool for exploring underwater acoustic signal behavior and beamforming concepts.

This **project aims** to simulate and visualize the behavior of directional sonar beamforming in underwater environments. It demonstrates how real-time animations and acoustic pressure modeling can be used to understand sonar signal dynamics, directional

1.3 Definitions

What is Beamforming?

Beamforming is a signal processing technique used in sensor arrays (like sonar or antennas) to focus the signal transmission or reception in a specific direction.

Why it's important in this project:

- It allows the sonar system to **"aim"** its energy towards a target.
- Increases detection accuracy and range by reducing noise from unwanted directions.

What is a Transponder?

A **transponder** is an underwater device that receives a sonar signal and automatically responds by sending a return signal.

In our simulation:

- The transponder is the **fixed red dot** at the bottom (6000m deep).
- It represents an underwater target, object, or marker.

Why Electric to Acoustic Signals?

Sonar systems convert **electrical signals** (generated from control systems) into **acoustic waves** using transducers.

In this project:

- We simulate this conversion using the formula: $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$

where Δp is the **acoustic pressure**.

- This models how **electrical energy becomes directional underwater sound waves**, which are used for detection.

Phase (θ)

Definition:
The phase of a wave tells us **where in its cycle** the wave is at a given time.

In your project:

- Used in the formula $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$
- **Phase shift (θ)** helps simulate delay or alignment between the signal and response.
- It affects **when** the wave starts oscillating within its sine curve.

Amplitude (A)

Definition:
Amplitude is the **maximum strength or height** of a wave.

In your simulation:

- A(α) changes based on the beam angle α.
- Higher amplitude → **Stronger acoustic pressure**
- Dictates the **intensity** of the sonar pulse in a given direction.

Range

Definition:
Range is the **distance** from the sonar source (boat) to the target (transponder).

In the animation:

- Distance between the boat and red transponder (usually around 6000 meters deep).
- Shown dynamically in the simulation as the beam tracks movement.

Chapter 2. System Design

2.1 System Architecture

The system is designed as a modular, Python-based simulation that visualizes the real-time interaction between an underwater transponder and a surface vessel. The architecture consists of three main components:

1. **Boat and Transponder Motion Module**
   Handles the movement of the surface vessel along the horizontal (X) axis and maintains the transponder's fixed underwater position. The boat motion is bi-directional and continuous, simulating a typical sonar scanning path.
2. **Sonar Beam Visualization Module**
   Generates and animates a directional sonar beam with a defined beamwidth ($\theta = 6°$). The beam is dynamically formed based on the position of the boat relative to the transponder. It includes directional indicators and angular markers for both the beam angle (θ) and the direction angle (α).
3. **Acoustic Signal and Pressure Modeling Module**
   Implements the signal model $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$, where $A(\alpha)$ is a direction-dependent amplitude function. This module computes the real-time acoustic pressure and displays key parameters such as frequency, amplitude, pressure, and range during the animation.

The simulation loop integrates these modules using Matplotlib for graphical rendering and interactive widgets for user control (pause/play and restart). The system captures both the mathematical and visual dynamics of sonar signal propagation, making it suitable for analysis, demonstration, and educational purposes.

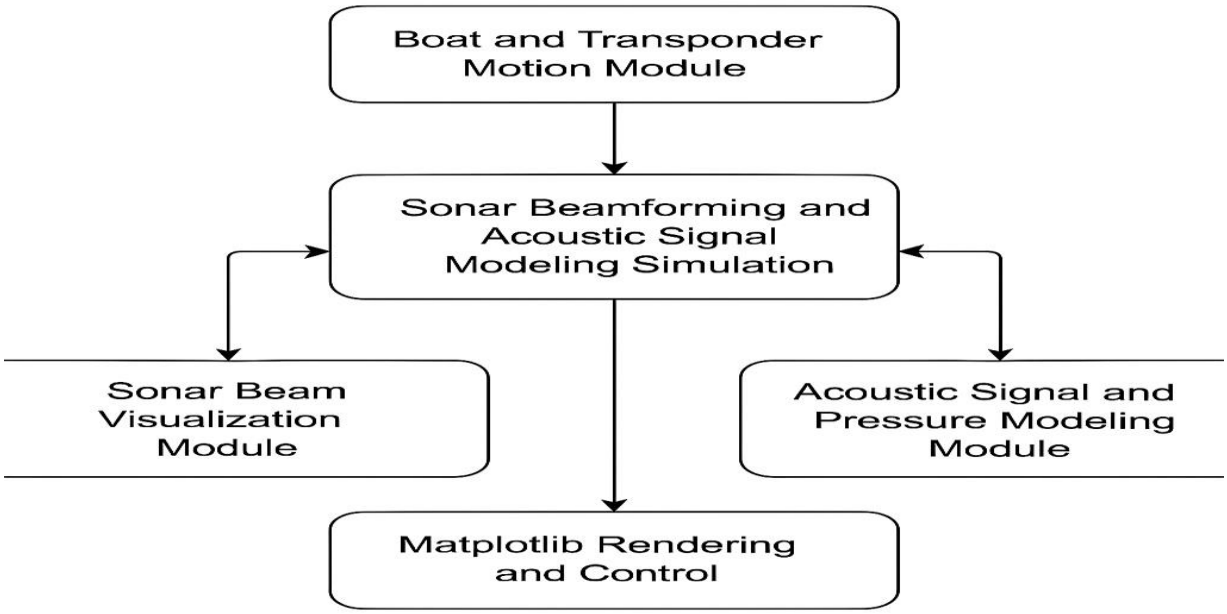


Fig2.1: data flow

2.2 Components & Modules

The system is divided into the following core components and modules, each responsible for a specific functionality in the sonar beamforming simulation:

1. Boat Motion Module

- Simulates a surface vessel moving horizontally over a defined sea surface.
- Handles boat position updates and direction reversal upon reaching the simulation boundary.
- Continuously triggers real-time updates to the beam and signal parameters.

2. Transponder Module

- Represents a stationary underwater acoustic beacon located at a fixed depth (6000 meters).
- Serves as the reference point for calculating beam angles and signal range.
- Plotted statically with clear annotation in the simulation.

3. Beamforming Module

- Generates a directional sonar beam with a specified beamwidth of 6°.
- Dynamically adjusts direction based on the boat's real-time position.
- Includes visual elements such as direction arrows and angle arcs.

4. Acoustic Pressure Calculation Module

- Implements the signal formula: $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$

where:

- $A(\alpha)=2.5(1+\cos(2(\alpha-90°)))$
- α is the direction angle from the transponder to the boat.

- Calculates pressure amplitude in real time and displays it along with frequency, range, and angle values.

5. User Interaction & Control Module

- Enables runtime controls using buttons:
  - **Pause/Play** to freeze or resume animation.
  - **Restart** to reset the boat position and simulation loop.
- Uses Matplotlib interactive widgets for user interface integration.

Each module is implemented in Python as separate functions or scripts, providing modularity, maintainability, and clarity. This design ensures that each element of the simulation contributes independently yet cohesively to the overall system behavior.

2.3 Workflow & Data Flow

The system follows a sequential and looped workflow:

1. **Initialization**
   - Set up boat position, transponder location, beam parameters, and animation environment.
2. **Frame Update Loop**
   - Calculate beam angle (α) based on current boat-transponder geometry.
   - Compute pressure (Δp) using the directional sinusoidal model.
   - Update the boat's direction and motion across the surface.
3. **User Control Monitoring**
   - Listen for button inputs to pause/play or restart the simulation.
4. **Real-Time Visualization**
   - Animate all visual elements: boat, beam, signal arc, text indicators, and transponder.

2.4 Technology Stack

Layer	Tools / Technologies
Programming Language	Python 3.11+
Visualization	Matplotlib
Animation Framework	Matplotlib Animation (FuncAnimation)
Numerical Computing	NumPy
Environment	VS Code
File Structure	Modular .py scripts
OS	Windows

2.5 Security & Performance Considerations

While this is a local simulation with no network interfaces, the following considerations were kept in mind:

- **File Access**: No external file dependencies reduce security risks.
- **Memory Usage**: Matplotlib animations can consume memory; data reuse is optimized within update functions.
- **Error Handling**: Edge cases like angle overflow or invalid pressure values are handled to prevent crashes.

2.6 Performance Optimization & Scalability

- **Optimized Calculations**: Signal calculations are vectorized where possible for efficiency.
- **Frame Rate**: The animation updates are set at a controlled interval to balance smooth visuals and CPU load.
- **Modularity**: Components are designed to allow extensions like 3D plots, sonar interference modeling, or OpenCV-based image overlays.

Chapter 3. Methodology

3.1 Problem Statement

Traditional sonar simulations often lack real-time visual feedback and dynamic modeling of acoustic pressure variations. This project addresses the gap by implementing a dynamic simulation that models directional beamforming and acoustic pressure propagation in underwater environments.

3.2 Mathematical Modeling

This section describes the mathematical foundation used to simulate the directional underwater sonar beam and the resulting acoustic pressure.

3.2.1 Acoustic Pressure Equation

The pressure variation from the sonar source is modeled using a time-varying sinusoidal function:

$$\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$$

Where:

- Δp: Instantaneous acoustic pressure (in Pascals)
- $A(\alpha)$: Directional amplitude as a function of beam angle α\alphaα
- ω: Angular frequency (in radians/sec), where $\omega = 2\pi f$

- t: Time (in seconds)
- θ: Phase offset (in radians)
- α: Beam angle in radians (converted to degrees for amplitude modeling)

3.2.2 Directional Amplitude Model

To model realistic directivity, a cosine-based function is used to vary the amplitude with beam angle:

$A(\alpha)=2.5\cdot(1+\cos(2(\alpha^\circ-90^\circ)))$

Where α° is the absolute beam angle in degrees.

This model ensures:

- Maximum pressure of **5 Pa** at **30° and 150°**
- Mid-level pressure of **2.5 Pa** at **90°**
- Directional symmetry around 90°, simulating realistic beamforming effects

3.2.3 Assumptions

- The medium (seawater) is assumed to be homogeneous.
- Pressure attenuation over distance is not modeled explicitly.
- Frequency f is fixed; variations in pressure are purely angular and time-dependent.
- Phase offset θ and frequency ω are user-defined for each simulation instance.

3.3 Simulation Logic

1. **Initialization**:
    - Boat, beam, transponder, and visual elements are initialized using Matplotlib.
2. **Looping Motion**:
    - The boat moves from left to right and reverses with dynamic direction flipping.
3. **Pressure Calculation**:
    - At each time frame, the current angle α\alphaα is calculated.
    - The sinusoidal pressure model is evaluated for real-time animation.
4. **User Controls**:
    - Play/Pause and Restart buttons allow dynamic control over the animation flow.

3.4 Beamforming Model

The beam is modeled using a fixed 6° beamwidth with four polar-style lobes. The beam range adapts dynamically based on the boat-transponder distance, maintaining realism in sonar coverage.

3.5 Visualization Pipeline

- **Boat Movement**: Controlled stepwise motion.
- **Signal Arc**: Visualizes the signal traveling through the beam.
- **Text Overlay**: Displays real-time values for beam angle, pressure, frequency, and boat X-position.

Chapter 4: Implementation and Analysis

4.1 Setup & Installation

To run the sonar beamforming simulation, the following setup steps were followed:

Software Dependencies

- **Python** 3.10 or above
- **Matplotlib** for 2D animation and visualization
- **NumPy** for numerical computation
- **VS Code** or any Python-compatible IDE

Installation Steps

1. Install Python from the official Python website.
2. Install required libraries using pip:

```
pip install matplotlib numpy
```

3. Clone or download the boat_simulation project folder into your local system.
4. Open the folder in VS Code or run the main file using:

```
python boat_simple_animation.py
```

4.2 File Structure

The project directory is organized as follows:

```
boat_simulation/
 ├── boat_simple_animation.py
 ├── electric_to_acoustic_signal.py
```

- **boat_simple_animation.py**: Contains the full animation loop, user interface buttons, beam direction logic, and signal rendering.
- **electric_to_acoustic_signal.py**: Modular script that models the directional acoustic pressure $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$.

4.3 Code Breakdown

This section provides a structured explanation of the core Python scripts used to implement and animate the directional sonar beamforming simulation and acoustic signal modeling.

4.3.1 electric_to_acoustic_signal.py – Signal Modeling

This module defines the mathematical model that simulates directional acoustic pressure generated by an underwater sonar beam.

```
import numpy as np

def electric_to_acoustic_signal(alpha_rad, omega_rad, t_sec, theta_rad):
    alpha_deg = np.abs(np.degrees(alpha_rad))
    if alpha_deg > 180:
        return 0.0
    amplitude = 2.5 * (1 + np.cos(np.radians(2 * (alpha_deg - 90))))
    phase = omega_rad * t_sec + theta_rad
    delta_p = amplitude * np.sin(phase)
    return delta_p
```

Explanation

- **Input Parameters**:
  - alpha_rad: Directional angle of the sonar beam in radians.
  - omega_rad: Angular frequency of the signal.
  - t_sec: Time in seconds.
  - theta_rad: Phase offset.
- **Amplitude Model**: Uses a cosine-based model to simulate directivity:

$$A(\alpha) = 2.5 \cdot (1 + \cos(2(\alpha - 90^\circ)))$$

- **Output**: Instantaneous acoustic pressure Δp based on time and angle.

4.3.2 boat_simple_animation.py – Main Simulation & Animation

This script contains the complete logic for plotting and animating the sonar beam, boat motion, and acoustic behavior over time.

Imports and Setup

```
import matplotlib.pyplot as plt

import numpy as np

from matplotlib.patches import Arc, FancyArrow, Circle

from electric_to_acoustic_signal import electric_to_acoustic_signal
```

- **Libraries**: Used for visualization (matplotlib), computation (numpy), and geometric elements (Arc, Arrow, etc.).
- **Function Import**: Brings in the signal model for real-time calculations.

System Parameters

```
beam_angle_deg = 6

depth = 6000

freq = 1

theta = np.radians(0)

omega = 2 * np.pi * freq
```

- Sets beam angle, ocean depth, frequency, and angular frequency.

Plot Initialization

```
fig, ax = plt.subplots()

ax.set_xlim(-30, 30)

ax.set_ylim(-6500, 100)

ax.axhline(0, color='blue', linestyle='--')        # Water surface

ax.axhline(-depth, color='red', linestyle=':')     # Transponder line
```

- Creates the canvas with axes limits and markers.

Dynamic Visual Elements

```
boat, = ax.plot([], [], marker='s', color='black', markersize=10)

beam = FancyArrow(...)

arc = Arc(...)
```

- **Boat**: Black square that moves along the surface.
- **Beam**: Yellow arrow representing sonar direction.
- **Arc**: Shows angular spread (6°) of the sonar beam.

Real-time Text Labels

```
text_pressure = ax.text(...)
```

```
text_beam = ax.text(...)
text_freq = ax.text(...)
text_range = ax.text(...)
```

- Updates in each frame with values such as:
    - Beam angle α
    - Acoustic pressure Δp
    - Frequency f
    - Beam range (distance to target)

Main Animation Loop

```
for i in range(frame_count):
    t = i / 20.0
    x = ...
    alpha = ...
    pressure = electric_to_acoustic_signal(alpha, omega, t, theta)
    update_plots()
```

- Time and beam angle update every frame.
- Signal computed using electric_to_acoustic_signal().

UI Buttons

```
pause_button = Button(...)
refresh_button = Button(...)
```

- **Pause/Play**: Temporarily stops the animation.
- **Refresh**: Restarts the simulation from the beginning.

Execution

```
ani = FuncAnimation(fig, update_frame, ...)
plt.show()
```

- Runs the animation using FuncAnimation.
- Opens the interactive window with all visuals.

4.3 Code Integration & Features

The simulation integrates physics-based modeling with interactive animation. Key features include:

- **Directional Beam Simulation**: A real-time beam visualized with 6° beamwidth, following the boat's path.
- **Acoustic Pressure Modeling**: Implemented via the formula

$$\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$$

where $A(\alpha) = 2.5 \cdot (1 + \cos(2(\alpha - 90^\circ)))$, allowing dynamic variation with beam angle.

- **Realistic Depth Modeling**: Fixed transponder depth of 6000 meters used to compute sonar range.
- **User Interface Controls**:
  - **Pause/Play Button**: Temporarily halts or resumes animation.
  - **Refresh Button**: Restarts simulation from initial state.
- **Bidirectional Looping**: Boat motion and beam direction flip seamlessly after each pass.

Code: boat_simple_animation.py

```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from matplotlib.patches import Polygon, FancyArrow
from matplotlib.widgets import Button
from electric_to_acoustic_signal import electric_to_acoustic_signal
paused = False
restart_requested = False
saved_data = []
def on_key(event):
    global paused
    if event.key == 'enter':
        paused = not paused
def on_restart(event):
    global restart_requested
    restart_requested = True
def on_pause_play(event):
    global paused
```

```
    paused = not paused
    pause_button.label.set_text("Play" if paused else "Pause")
def save_data_to_excel():
    df = pd.DataFrame(saved_data)
    df.to_excel("sonar_simulation_data.xlsx", index=False)
    print("Data saved to sonar_simulation_data.xlsx")
def plot_transponder(ax, x=0, z=-5000, radius=100):
    from matplotlib.patches import Circle
    circle = Circle((x, z), radius, color='red')
    ax.add_patch(circle)
    ax.text(x + 200, z, "Transponder", fontsize=9, color='red')
def simulate_boat():
    global paused, restart_requested, pause_button
    boat_length = 2000
    boat_radius = 250
    beam_angle_deg = 6
    beam_angle_rad = np.radians(beam_angle_deg)
    virtual_beam_angle_rad = np.radians(40)
    x_vals = np.linspace(-6000, 6000, 200)
    z_boat = -50
    trans_x, trans_z = 0, -5000


    fig, ax = plt.subplots()
    fig.set_size_inches(14, 6)
    fig.canvas.mpl_connect('key_press_event', on_key)
    ax_button_restart = plt.axes([0.90, 0.80, 0.08, 0.05])
    button_restart = Button(ax_button_restart, 'Restart', color='lightgray', hovercolor='lightblue')
    button_restart.on_clicked(on_restart)
    ax_button_pause = plt.axes([0.90, 0.72, 0.08, 0.05])
    pause_button = Button(ax_button_pause, 'Pause', color='lightgray', hovercolor='lightblue')
    pause_button.on_clicked(on_pause_play)
```

```
ax_save = plt.axes([0.90, 0.64, 0.08, 0.05])
btn_save = Button(ax_save, 'Save')
btn_save.on_clicked(lambda event: save_data_to_excel())
text_pressure = fig.text(0.01, 0.90, "", fontsize=11, color='purple', ha='left')
text_beam = fig.text(0.01, 0.80, "", fontsize=11, color='darkblue', ha='left')
text_boatx = fig.text(0.01, 0.70, "", fontsize=11, color='black', ha='left')
text_freq = fig.text(0.01, 0.60, "", fontsize=11, color='black', ha='left')
text_range = fig.text(0.01, 0.50, "", fontsize=11, color='red', ha='left')
direction = 1
i = 0
while True:
    while paused:
        plt.pause(0.1)
    if restart_requested:
        i = 0
        direction = 1
        restart_requested = False
    boat_x = x_vals[i]
    ax.clear()
    ax.set_xlim(-6000, 6000)
    ax.set_ylim(-6000, 500)
    ax.set_aspect('equal')
    xticks = ax.get_xticks()
    yticks = ax.get_yticks()
    ax.set_xticks(xticks)
    ax.set_xticklabels([str(abs(int(label))) for label in xticks])
    ax.set_yticks(yticks)
    ax.set_yticklabels([str(abs(int(label))) for label in yticks])
    ax.set_title("Boat And Beam Simulation")
    ax.set_xlabel("X (distance in meters)")
    ax.set_ylabel("Z (depth in meters)")
```

```
ax.grid(True)
ax.axhline(y=0, color='blue', linestyle='-', linewidth=1.5)
ax.fill_between(np.linspace(-6000, 6000, 500), -7000, 0, color='skyblue', alpha=0.3)
x_profile = np.linspace(-0.5 * boat_length, 0.5 * boat_length, 200)
z_half = boat_radius * np.sqrt(1 - (x_profile / (0.5 * boat_length)) ** 2)
x_hull = np.concatenate([x_profile, x_profile[::-1]])
z_hull = np.concatenate([z_half, -z_half[::-1]])
ax.fill(x_hull + boat_x, z_hull + z_boat, color='black')
dx = boat_x - trans_x
dz = z_boat - trans_z
distance = np.sqrt(dx ** 2 + dz ** 2)
beam_radius = np.tan(beam_angle_rad) * distance
beam = Polygon([
    [trans_x, trans_z],
    [boat_x - beam_radius, z_boat],
    [boat_x + beam_radius, z_boat]
], closed=True, color='lightgreen', alpha=0.5)
ax.add_patch(beam)
arrow_dx = dx * 0.9
arrow_dz = dz * 0.9
ax.add_patch(FancyArrow(
    trans_x, trans_z,
    arrow_dx, arrow_dz,
    width=10, head_width=80, head_length=100,
    color='red', alpha=0.8
))
arc_len = 400
angle = np.arctan2(dz, dx)
arc_range = np.linspace(-beam_angle_rad, beam_angle_rad, 100)
arc_x = trans_x + arc_len * np.cos(angle + arc_range)
arc_z = trans_z + arc_len * np.sin(angle + arc_range)
```

```
    ax.plot(arc_x, arc_z, color='darkgreen', linewidth=2)
    label_idx = len(arc_x) // 2
    ax.text(arc_x[label_idx] + 200, arc_z[label_idx] + 200, r'$\theta = 6^\circ$', fontsize=10,
color='green')
    mid_x = (boat_x + trans_x) / 2
    mid_z = (z_boat + trans_z) / 2
    ax.text(mid_x, mid_z, f"R = {distance:.1f} m", fontsize=10, color='red', weight='bold')
    plot_transponder(ax, x=trans_x, z=trans_z)
    arrow_dx_dir = 700 if direction == 1 else -700
    ax.add_patch(FancyArrow(boat_x, z_boat + boat_radius + 90,
                            arrow_dx_dir, 0,
                            width=30, head_width=60, head_length=80, color='orange'))
    alpha = np.arctan2(dz, dx)
    alpha_deg = np.degrees(alpha)
    if alpha_deg < 0:
       alpha_deg += 360
    t = i / 30.0
    freq = 1.0 - 0.5 * np.sin(alpha)
    omega = 2 * np.pi * freq
    amplitude = 5 - 2.5 * np.cos(np.radians((alpha_deg - 90) * 180 / 90))
    raw_signal = amplitude * np.sin(omega * t + virtual_beam_angle_rad)
    signal = abs(raw_signal)
    arc_len_alpha = 300
    arc_range_alpha = np.linspace(0, alpha, 100)
    arc_x_alpha = trans_x + arc_len_alpha * np.cos(arc_range_alpha)
    arc_z_alpha = trans_z + arc_len_alpha * np.sin(arc_range_alpha)
    ax.plot(arc_x_alpha, arc_z_alpha, color='orange', linewidth=2)
    label_idx_alpha = len(arc_x_alpha) // 2
    ax.text(arc_x_alpha[label_idx_alpha] + 100,
          arc_z_alpha[label_idx_alpha] + 100,
          rf'$\alpha$ = {alpha_deg:.1f}°',
```

```
        fontsize=10, color='orange')
    text_pressure.set_text(f"Acoustic Pressure (Δp) = {signal:.4f}")
    text_boatx.set_text(f"Boat X Position = {abs(boat_x):.1f} m")
    text_beam.set_text(f"Beam angle (deg) = {alpha_deg:.1f}°")
    text_freq.set_text(f"Frequency f (Hz)= {freq:.2f} Hz")
    text_range.set_text(f"Range (Distance) = {distance:.1f} m")
    print(f"Step {i+1}/{len(x_vals)}:")
    print(f"    Boat X Position     : {abs(boat_x):.2f}")
    print(f"    Beam Angle α (deg)  : {alpha_deg:.2f}")
    print(f"    Frequency f (Hz)    : {freq:.2f}")
    print(f"    Amplitude A_m(α)    : {amplitude:.4f}")
    print(f"    Range (Distance)    : {distance:.2f} m")
    print(f"    Acoustic Pressure (Δp): {signal:.4f}")
    print("-------------------------------------------------")
    saved_data.append({
       "Time (s)": t,
       "Acoustic Pressure (Δp)": signal,
       "Beam Angle (°)": alpha_deg,
       "Frequency (Hz)": freq,
       "Range (m)": distance,
       "Boat X Position (m)": boat_x
       })
    plt.draw()
    plt.pause(0.01)
    if direction == 1:
       i += 1
       if i == len(x_vals) - 1:
          direction = -1
    else:
       i -= 1
       if i == 0:
```

```
            direction = 1

    plt.show()

simulate_boat()
```

code: electric_to_acoustic_signal.py

```
import numpy as np

def electric_to_acoustic_signal(alpha_rad, omega_rad, t_sec, theta_rad):
    alpha_deg = np.abs(np.degrees(alpha_rad))
    if alpha_deg > 180:
        return 0.0
    amplitude = 2.5 * (1 + np.cos(np.radians(2 * (alpha_deg - 90))))
    phase = omega_rad * t_sec + theta_rad
    delta_p = amplitude * np.sin(phase)
    return delta_p
```

Chapter 5: Observations

This section presents the key visual and analytical outcomes of the simulation, along with technical insights drawn from observing the system in real-time.

5.1 Visual Outcomes

- **Directional Beam Rendering**:
  The simulation successfully visualizes the sonar beam originating from the underwater transponder and reaching the moving surface vessel. The beam dynamically adjusts its angle and range in sync with the vessel's position and motion.
- **Real-Time Signal Updates**:
  Key parameters such as acoustic pressure (Δp), beam angle (α), frequency (f), and range are displayed and updated in real time, enhancing interpretability of underwater signal behavior.
- **Dynamic Acoustic Pressure**:
  The pressure variations, governed by the sinusoidal model

  $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$

were observed to behave as expected:

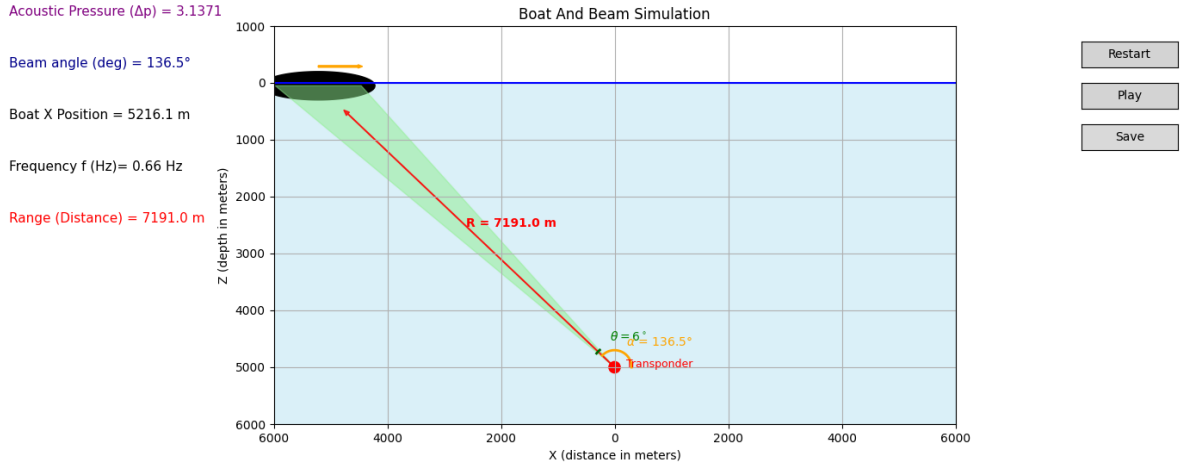
- Maximum (5 Pa) at 30° and 150°
- Minimum (2.5 Pa) at 90°
- Zero transitions and phase shifts aligned with theory

5.2 Functional Observations

- **Accuracy**:
  The amplitude model and beam angle calculation closely mimic real-world directional sonar behavior with an ideal 6° beamwidth.
- **Smooth Animation**:
  The boat's motion and signal updates are synchronized frame-by-frame, ensuring smooth transitions and real-time simulation fidelity.
- **Pause/Restart Interactivity**:
  UI controls for pausing and restarting allow focused observation of any stage in the simulation, making it interactive and demonstrative for presentations.

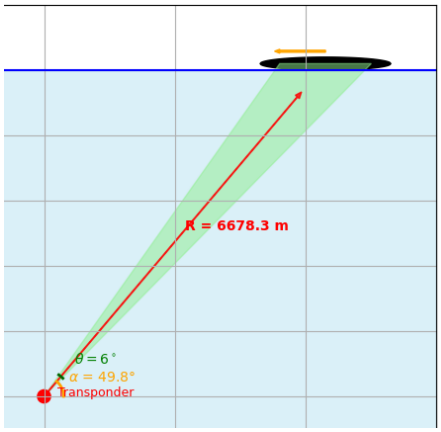
5.2.1 Figure 1: Initial Simulation Setup

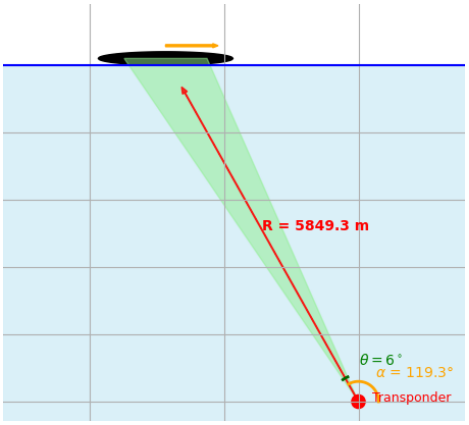
- Shows: boat on surface, transponder at depth, beam starting position.



5.2.1 Figure 2: arrow of the boat direction

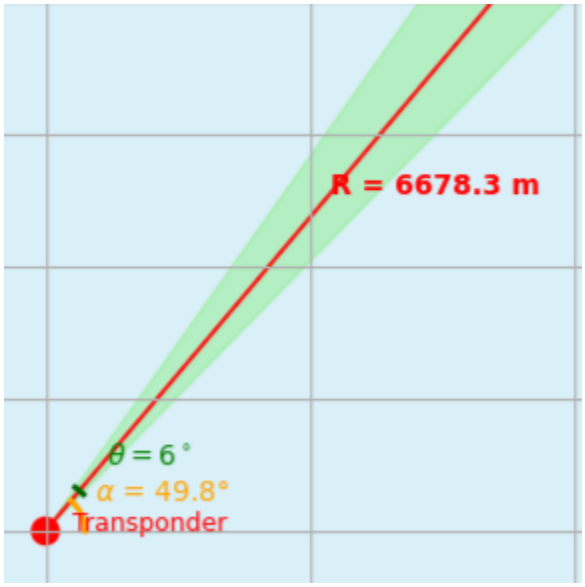
- One frame where the directional beam pattern is visible.
- Shows how the beam follows the boat’s orientation.

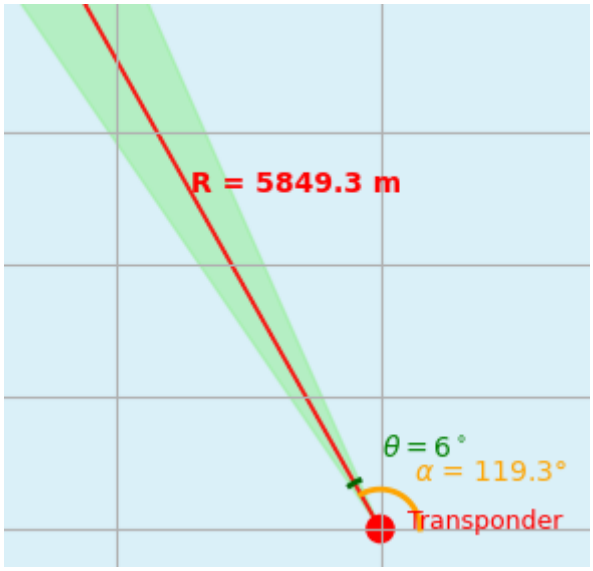




5.2.3 Figure 3: Moving Signal Arc

- Capture a moment where the signal arc is moving from transponder to boat along the beam.
- Highlights dynamic signal propagation.





5.2.4 Figure 4: Pressure Reading (Δp) Display

- Annotated screenshot with Δp value shown on-screen.
- Preferably when α = 40°, 90°, and 130° for variation in amplitude.

α = 130°

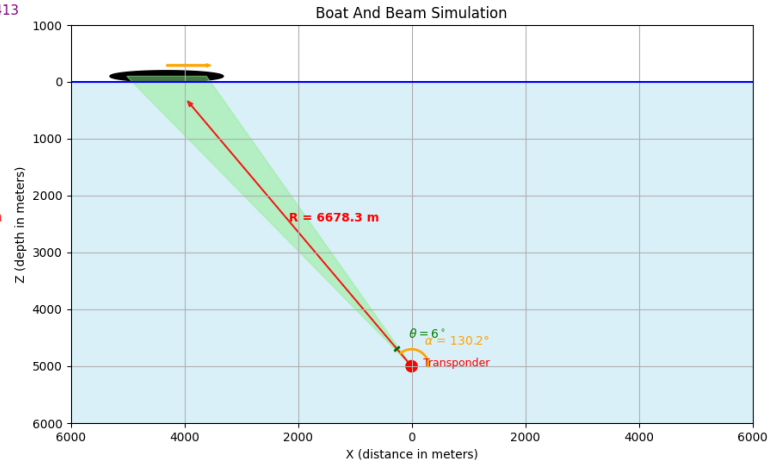
Acoustic Pressure (Δp) = 4.2413

Beam angle (deg) = 130.2°

Boat X Position = 4311.6 m

Frequency f (Hz)= 0.62 Hz

Range (Distance) = 6678.3 m



α = 90°

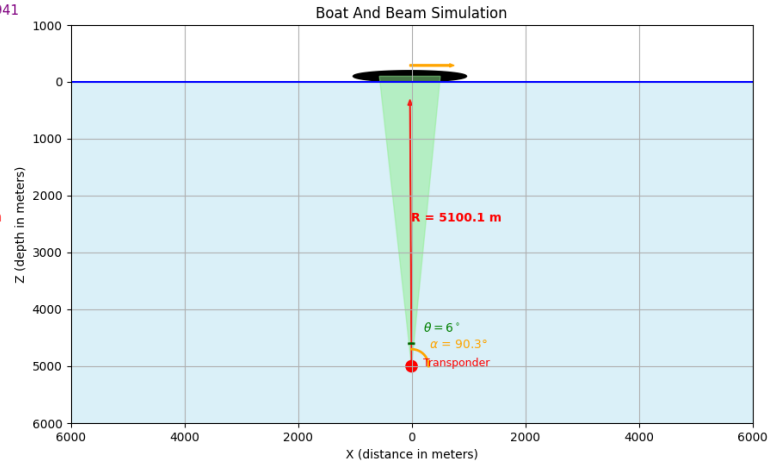
Acoustic Pressure (Δp) = 2.4941

Beam angle (deg) = 90.3°

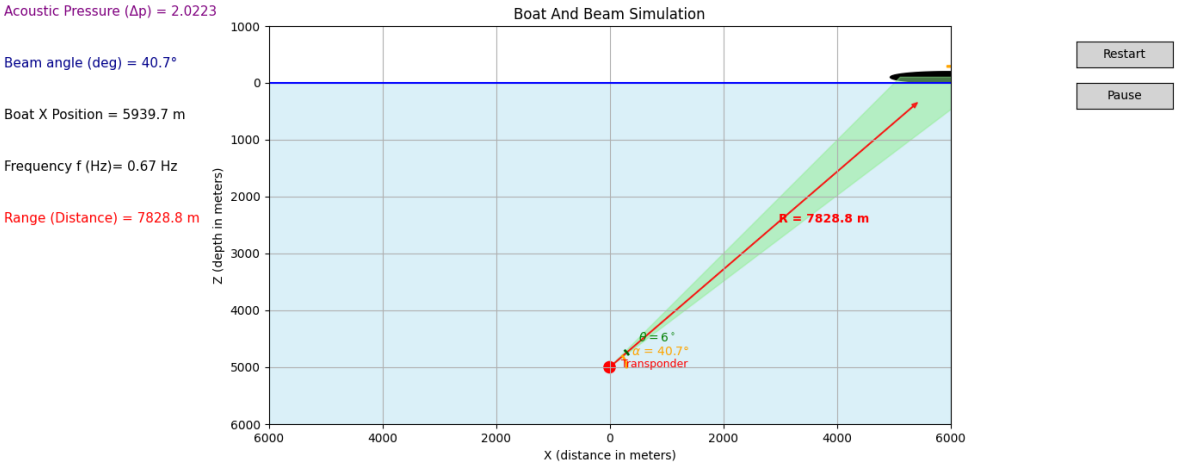
Boat X Position = 30.2 m

Frequency f (Hz)= 0.50 Hz

Range (Distance) = 5100.1 m

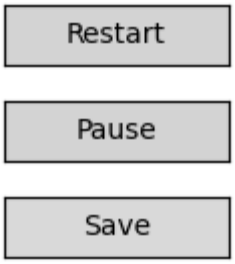


α = 40°



5.2.5 Figure 5: Pause/Play and Refresh Buttons

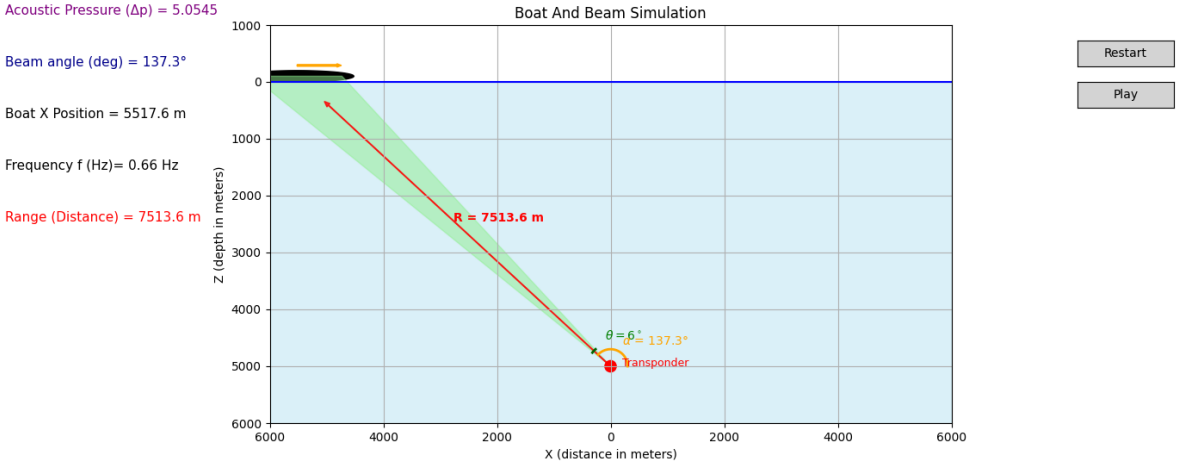
- Include a figure showing the simulation GUI with added controls.



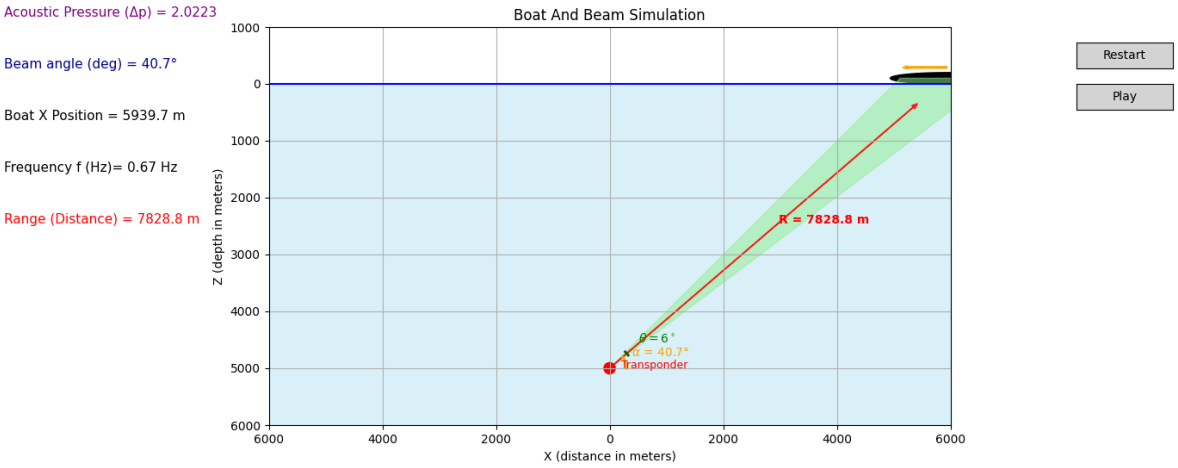
5.2.6 Figure 6: Full Beam Range to Seabed

- A frame where the beam clearly reaches from boat to transponder (5000m depth).

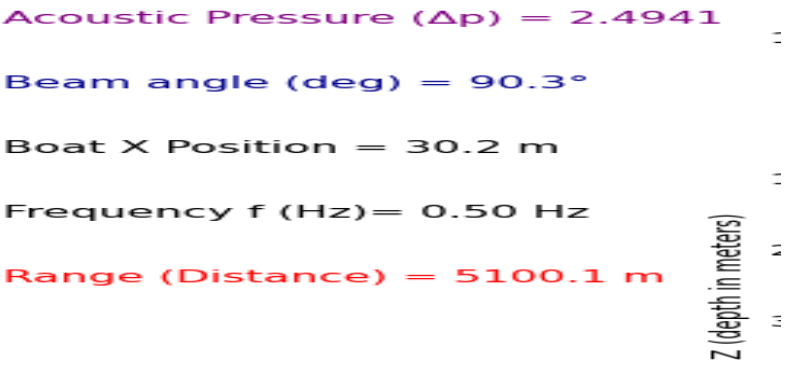
Start:



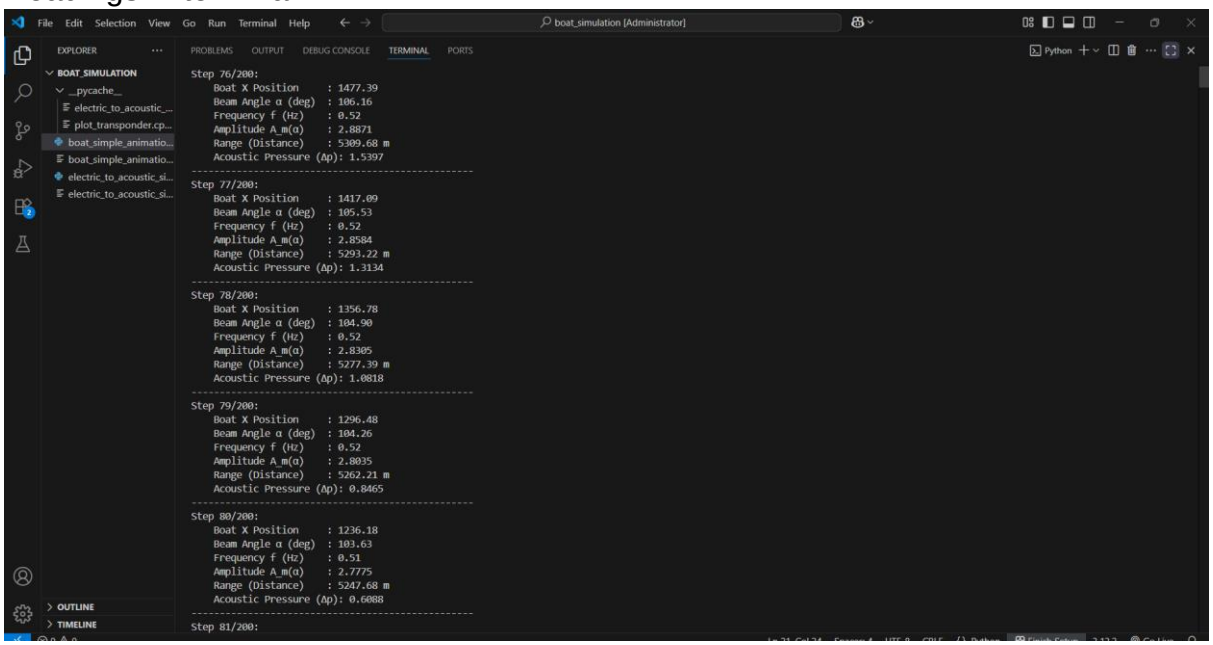
End:



Readings:



Readings in terminal:



5.2.7 Figure 7: sonar_simulation_data.xlxs

	A	B	C	D	E	F
1	**Time (s)**	**Acoustic Pressure (Δp)**	**Beam Angle (°)**	**Frequency (Hz)**	**Range (m)**	**Boat X Position (m)**
2	0	3.472825656	139.6354634	0.67617579	7874.642849	-6000
3	0.033333333	4.002455433	139.3496405	0.674279341	7828.794172	-5939.698492
4	0.066666667	4.445105147	139.0604574	0.672368845	7783.142611	-5879.396985
5	0.1	4.794180388	138.7678694	0.67044435	7737.691657	-5819.095477
6	0.133333333	5.045242262	138.4718317	0.668505911	7692.444864	-5758.79397
7	0.166666667	5.196002963	138.1722988	0.666553594	7647.405857	-5698.492462
8	0.2	5.246273984	137.8692253	0.664587474	7602.578329	-5638.190955
9	0.233333333	5.197871053	137.5625653	0.66260764	7557.966042	-5577.889447
10	0.266666667	5.054480675	137.2522725	0.66061419	7513.57283	-5517.58794
11	0.3	4.82149374	136.9383006	0.658607236	7469.4026	-5457.286432
12	0.333333333	4.505812082	136.6206029	0.656586901	7425.459331	-5396.984925
13	0.366666667	4.115634096	136.2991327	0.654553323	7381.747076	-5336.683417
14	0.4	3.660225596	135.9738429	0.652506652	7338.269963	-5276.38191
15	0.433333333	3.149681998	135.6446864	0.650447053	7295.032197	-5216.080402
16	0.466666667	2.594687671	135.3116159	0.648374708	7252.038059	-5155.778894
17	0.5	2.006277926	134.9745842	0.646289811	7209.291907	-5095.477387
18	0.533333333	1.395608672	134.6335438	0.644192576	7166.798179	-5035.175879
19	0.566666667	0.77373817	134.2884475	0.64208323	7124.561391	-4974.874372
20	0.6	0.151424734	133.939248	0.639962021	7082.586141	-4914.572864
21	0.633333333	0.461056459	133.585898	0.637829213	7040.877105	-4854.271357
22	0.666666667	1.054074951	133.2283504	0.635685091	6999.439043	-4793.969849
23	0.7	1.61878318	132.8665585	0.633529957	6958.276796	-4733.668342
24	0.733333333	2.147230116	132.5004754	0.631364134	6917.395288	-4673.366834
25	0.766666667	2.632449861	132.1300549	0.629187969	6876.799525	-4613.065327
26	0.8	3.068525312	131.7552508	0.627001826	6836.494598	-4552.763819
27	0.833333333	3.450627533	131.3760177	0.624806095	6796.485682	-4492.462312
28	0.866666667	3.775031946	130.9923103	0.622601188	6756.778033	-4432.160804
29	0.9	4.039112878	130.6040841	0.620387541	6717.376996	-4371.859296

Chapter 6: Future Work

While this project successfully models directional underwater sonar beamforming with dynamic acoustic pressure visualization, there are several directions in which the simulation can be enhanced and expanded:

1. Multi-Beam Array Simulation

Integrating a phased array of transducers with adjustable phases and delays can simulate complex beam steering and scanning techniques used in modern sonar systems.

2. Environmental Modeling

Incorporating realistic underwater conditions such as salinity, temperature gradients, and ocean currents could refine the accuracy of beam propagation and signal attenuation.

3. Obstacle & Target Detection

Introducing underwater targets or obstacles would allow the simulation to explore sonar reflection, object detection, and signal loss, making it closer to real-world sonar operations.

4. Machine Learning for Beam Optimization

AI models could be trained on acoustic data to optimize beam direction or adapt to noisy environments, improving detection accuracy in dynamic ocean conditions.

5. 3D Simulation and Deployment

Extending the simulation into a 3D environment, along with integration into real-time underwater drones or robotic systems, could make this system applicable for live field testing and research deployments.

Chapter 7: Conclusion

This project successfully demonstrates a dynamic simulation of underwater sonar beamforming with integrated acoustic pressure modeling. The simulation integrates

mathematical modeling, signal processing, and visualization to mimic how a sonar beam behaves directionally in underwater environments.

Key Achievements of This Project Include:

- **Directional Beamforming Simulation**
  Modeled a dynamic sonar beam with adjustable directionality, beamwidth, and lobe patterns based on real-time motion.
- **Acoustic Pressure Modeling**
  Implemented a sinusoidal pressure model with directional amplitude variation, representing realistic underwater acoustic behavior.
- **Mathematical Accuracy**
  Incorporated signal equations: $\Delta p = A(\alpha) \cdot \sin(\omega t + \theta)$

where $A(\alpha)$ reflects direction-dependent pressure based on the beam angle α.

- **Interactive Visualization**
  Built a live Python-based animation using matplotlib to visualize boat motion, beam direction, signal propagation, and transponder targeting.
- **Modular System Design**
  Structured the project into reusable modules for signal modeling and animation, enabling easy extension and future upgrades.

This simulation provides a strong foundation for further advancements in underwater communication systems, sonar development, and acoustic-based research tools. It bridges theoretical acoustics with hands-on, programmable simulation—demonstrating the synergy between engineering, coding, and scientific modeling.

References

These cover sonar systems, beamforming theory, underwater acoustics, and related Python tools:

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