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ACOUSTIC LEAKY WAVES ANTENNA FOR UNDERWATER APPLICATIONS: ANALYSIS AND PERFORMANCE

María Campo-Valera[1], Rafael Asorey-Cacheda[2,3]

[1] *School of Engineering and Technology (ESIT), Universidad Internacional de la Rioja (UNIR), 26006 Logroño, Spain*

[2] *Department of Information and Communication Technologies, Universidad Politécnica de Cartagena member of European University of Technology EUt+, 30202 Spain*

[3] *People Oriented Smart Technologies Laboratory, European Research Group, European University of Technology,European Union*

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Abstract

Acoustic Leaky Wave Antennas (ALWAs) offer an effective approach for directional sound radiation in underwater environments. This work analyzes their behavior in a fluid medium, focusing on fluid–structure interaction mechanisms that control acoustic leakage and beam steering. Key performance metrics, such as far-field radiation patterns, are assessed, demonstrating the potential of ALWAs for underwater communication, sensing, and sonar applications.

Keywords: *underwater acoustics communication, leaky wave antennas, beamforming, sonar*

1. Introduction

Acoustic Leaky Wave Antennas (ALWAs) enable directional sound radiation through controlled leakage of guided waves [1], [2]. Their radiation angle depends on frequency, allowing passive beam steering.

While initially developed for electromagnetics [3], [4], ALWAs have been adapted to acoustics using metamaterials [5], [6]. In underwater environments, their behavior is strongly influenced by fluid–structure interaction, which modifies propagation and radiation characteristics .

Recent designs incorporate elastic resonant elements to enhance radiation efficiency and enable beam steering in water [7]. These systems offer compact and passive alternatives for sonar and underwater communication [8].

In this work, a full-wave numerical model based on the finite element method (FEM) is developed to analyze an ALWA operating in seawater. The model captures the coupling between elastic waves in the structure and acoustic radiation in the surrounding fluid. Radiation patterns are evaluated to assess performance in realistic underwater conditions.

Corresponding author: *mariamercedes.campo@unir.net.*

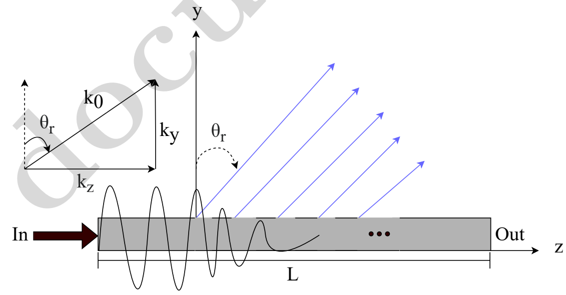

Figure 1: Illustration of an ALWA structure composed of a waveguide aligned along the z-axis with radiating openings. The diagonal blue lines represent emitted acoustic beams.

2. Theory

ALWAs radiate energy through controlled leakage of guided waves along a periodic structure [9]. In underwater environments, this mechanism is strongly influenced by fluid–structure interaction, which governs both radiation efficiency and beam direction.

As illustrated in *Figure 1*, the periodic openings along the waveguide allow acoustic energy to leak into the surrounding fluid, generating directional radiation.

The radiated pressure field is given by [9]:

$$P(z, y) = p_0\, e^{-j\, k_y\, y} e^{-j\, k_z\, z} e^{j\omega t}, \qquad (1)$$

where $k_z = \beta - j\alpha$ describes propagation and attenuation along the waveguide, and $k_y = \sqrt{k_0^2 - \beta^2}$

governs radiation into the fluid. Radiation occurs when $\beta < k_0$, with angle [9]:

$$\theta_r = \sin^{-1}\left(\frac{\beta}{k_0}\right) \tag{2}$$

The beamwidth is approximated as [9]:

$$\Delta\theta \approx \frac{\lambda}{L\cos(\theta_r)} \tag{3}$$

This frequency-dependent behavior enables beam steering, which is particularly relevant in underwater acoustics for adaptive directivity.
As a brief validation, the radiation angle predicted by Eq. (2) at selected frequencies within the study range is compared with the beam direction obtained from the FEM simulation. For instance, at 8450 Hz, the analytically estimated angle θ_r is consistent with the simulated main lobe direction shown in Figure 7, providing a first-order confirmation of the numerical model.

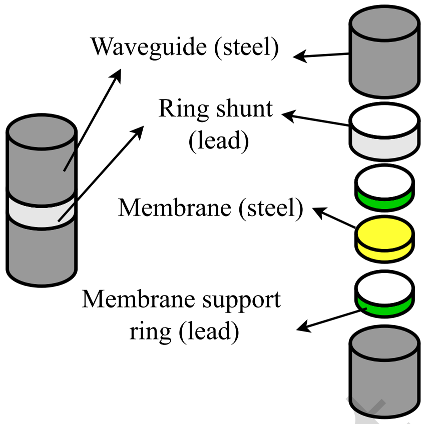

Figure 2: Parts of a unit cell that make up the proposed antenna.

3. Materials and Methods

This section describes the FEM simulation used to analyze the ALWA in an underwater environment, emphasizing fluid–structure interaction effects in seawater.

3.1. Modules

The model combines pressure acoustics and structural mechanics within a coupled FEM formulation. The acoustic field is governed by the Helmholtz equation, while the structural response follows linear elasticity. This coupled approach enables accurate representation of the interaction between the antenna structure and the surrounding fluid, which is essential for predicting underwater acoustic radiation.

3.2. Geometry

The simulated antenna consists of a periodic arrangement of unit cells, as shown in *Figure 2*. Each unit cell integrates a steel waveguide (dark gray) with a lead-based leakage element that promotes controlled acoustic radiation.
Figure 3 shows a detailed representation that includes the geometric parameters, which define the dimensions that determine the resonant behavior of the structure for a unit cell.
The introduction of internal resonant elements enables efficient coupling between elastic waves and the surrounding fluid, enhancing acoustic leakage in underwater conditions.
The numerical values of the geometric parameters used in the model are summarized in *Table 1*.

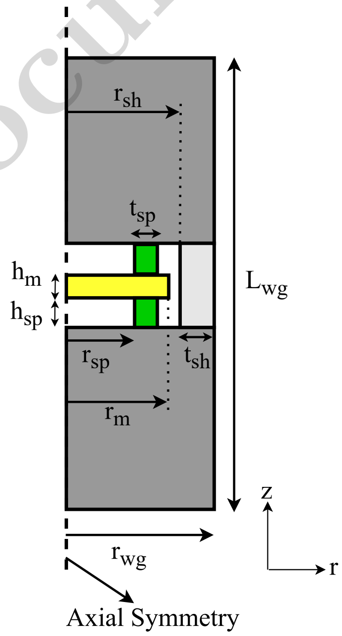

Figure 3: Schematic representation of a unit cell with geometric parameters.

3.3. Materials

The antenna is composed of steel and lead to balance stiffness and compliance. Steel ensures efficient wave propagation, while lead enhances local resonances and acoustic coupling.
The material properties used in the underwater model are listed in *Table 2*, including seawater parameters required to accurately represent acoustic propagation.

3.4. Physical Characterization of the Model

The model includes coupled pressure acoustic in the frequency domain, and solid mechanical physics to represent wave propagation and radiation in a submerged environment. Boundary conditions are defined to accurately simulate excitation, radiation, and fluid–structure interaction.

Table 1: Geometric parameters of the proposed antenna.

Variable	Description	Value
r_{wg}	Radius of the unit cell	49.6 mm
L_{wg}	Length of the unit cell	72.7 mm
r_{sh}	Radius of the leakage	41.6 mm
t_{sh}	Thickness of the leakage ring	7.9 mm
r_{sp}	Radius of the ring supporting the membrane	37.1 mm
t_{sp}	Thickness of the membrane support ring	3.1 mm
h_{sp}	Separation between membrane and waveguide	8.7 mm
h_m	Thickness of the membrane	12.2 mm
r_m	Radius of the membrane	40.3 mm
N	Number of cells	40

Table 2: Material properties of the proposed antenna.

Variable	Description	Value
ρ_{Pb}	Density of lead	11 340 kg m^{-3}
E_{Pb}	Young's module of lead	16.3 GPa
ν_{Pb}	Poisson's ratio of lead	0.44
ρ_{Steel}	Density of steel	7850 kg m^{-3}
E_{steel}	Young's module of steel	200 GPa
ν_{steel}	Poisson's ratio of steel	0.3
c	Speed of sound of seawater	1500 m s^{-1}
ρ	Density of seawater	1027 kg m^{-3}

3.4.1. Pressure Acoustics, Frequency Domain

Port boundary conditions are used to excite the antenna and analyze acoustic wave propagation in seawater. These ports define the input and output of the waveguide, enabling the evaluation of transmission and reflection behavior.
To simulate an open underwater environment, a **Perfectly Matched Boundary (PMB)** condition is applied at the outer limits of the acoustic domain. This condition acts as an absorbing layer that prevents artificial reflections, allowing outgoing waves to leave the computational domain without distortion. This is particularly important in underwater acoustics, where

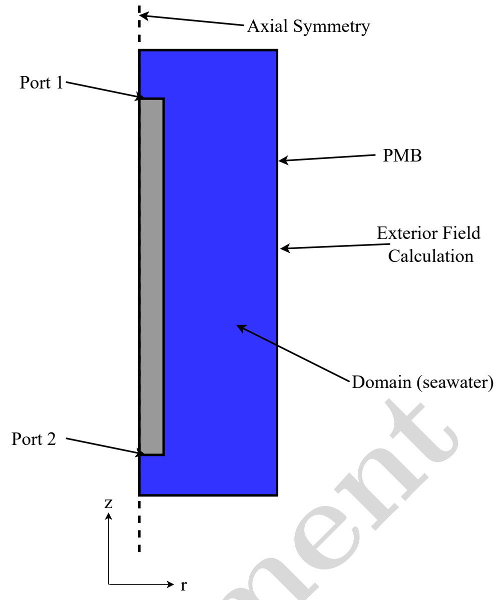

Figure 4: ALWA boundary conditions with Pressure Acoustics module

reflections from truncated domains can significantly alter radiation patterns and directivity.
In addition, the **Exterior Field Calculation** condition is used to evaluate the far-field acoustic radiation. This formulation computes the radiated pressure at large distances from the antenna based on the near-field solution, enabling accurate determination of radiation patterns and directivity without requiring an excessively large computational domain.
These boundary conditions are illustrated in *Figure 4*, where the excitation, absorption, and radiation regions are defined.

3.4.2. Solid Mechanics

The structural response is modeled using linear elasticity, enabling the computation of displacements, stresses, and strains within the antenna.
This formulation captures the dynamic behavior of the elastic components, which directly influences acoustic radiation through fluid–structure interaction. The mechanical boundary conditions applied to the structure are shown in *Figure 5*.

3.4.3. Multiphysics

The acoustic–structure coupling enforces continuity of pressure and normal acceleration at the fluid–solid interface. This bidirectional interaction allows the structural vibrations to generate acoustic waves in the fluid, while the fluid loading affects the structural response.
Such coupling is essential in underwater acoustics, where the surrounding medium strongly influences radiation efficiency, beam direction, and overall antenna performance.

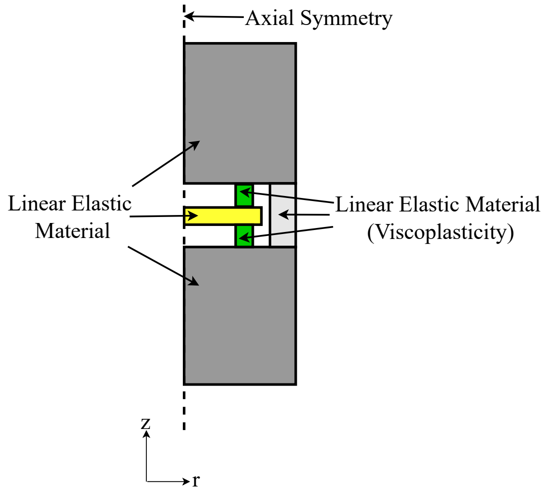

Figure 5: ALWA boundary conditions with Solid Mechanic module

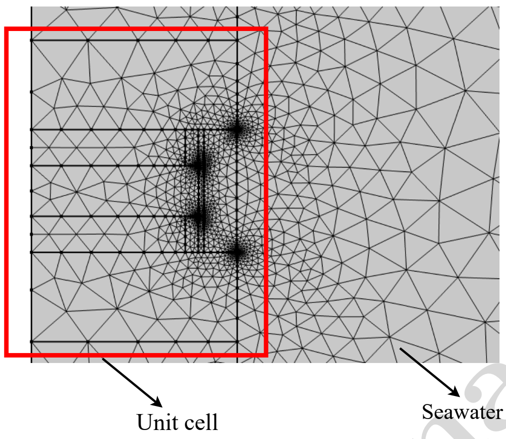

Figure 6: Meshing of the proposed ALWA antenna

3.5. Mesh

The finite element mesh is designed to resolve both acoustic and elastic wave propagation, with particular refinement near the fluid–structure interface.
A resolution criterion of approximately $\lambda/10$ is used in seawater to ensure numerical accuracy.

$$\Delta x = \frac{c}{10 \cdot f_{\max}} \approx 0.0158\,\mathrm{m} \tag{4}$$

where $c = 1500\,\mathrm{m/s}$ is the speed of sound in water and $f_{\max} = 9500\,\mathrm{Hz}$ is the maximum excitation frequency. Additional local refinements are applied in regions with high gradients, such as the resonant cavity and leakage elements.
A representative mesh is shown in *Figure 6*.

3.6. Study

The frequency range from 7800 Hz to 9500 Hz was selected to cover the regime in which the structure's

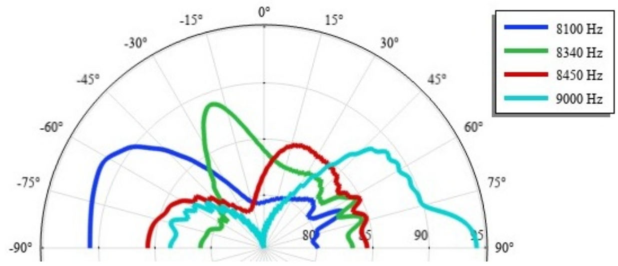

Figure 7: Far-field radiation pattern of the ALWA at selected frequencies (normalized pressure, linear scale). The diagram illustrates frequency-dependent beam steering across the analyzed frequency range.

geometric periodicity enables effective acoustic leakage into the surrounding medium, corresponding to the operational band of the proposed unit cell dimensions. This approach provides direct access to amplitude and phase information of the radiated field, which is essential for evaluating directivity and radiation efficiency in underwater environments.

4. Results and Discussion

This section summarizes the key numerical results obtained from the FEM simulation of the complete ALWA, focusing on its performance in underwater environments.

4.1. Radiation Pattern

The radiation pattern, shown in *Figure 7*, illustrates the frequency-dependent beam steering of the antenna. At lower frequencies, e.g., 8100 Hz, the main lobe points backward with a broad beam, while intermediate frequencies 8340 Hz–8450 Hz shift the beam forward with varying directivity. At higher frequencies 9000 Hz. Overall, The main lobe shifts approximately from $-60°$ at 8100 Hz to nearly $0°$–$15°$ at 9000 Hz, representing a total beam steering range of roughly $60°$–$75°$ across the analyzed frequency band. The radiation becomes highly focused, demonstrating the ALWA's ability to dynamically control the acoustic beam direction through frequency tuning.
These numerical results indicate the antenna's capability for frequency-dependent beam steering, highlighting its potential for spatial localization and directional communication in underwater applications.

5. Conclusion

This study demonstrates that ALWAs can effectively steer sound in underwater environments through frequency-dependent beam control. FEM simulations of the complete antenna reveal its capability to generate directional radiation, achieve high directivity, and adapt the beam angle across a range of frequencies.
The results highlight the potential of ALWAs for underwater applications, including spatial localization, communication, and sensing, where precise beam steering and compact, passive designs are essential.

Experimental validation of the simulated results remains an important direction for future work, and is planned to further confirm the antenna's performance under realistic conditions.

6. Acknowledgments

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