Acoustic Amplifier for Underwater Communication

CP301-Development Project Report

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Abstract

This project designs an acoustic amplifier for underwater communication, comprising a hydrophone preamplifier, bandpass filter, and power amplifier. Due to component unavailability, the focus shifted to theoretical design, LTspice simulations, and PCB design. The TI JFE150 preamplifier, Sallen-Key 4th-order bandpass filter, and TI TPA3116D2 power amplifier were selected for their performance in underwater applications. Simulations validate the design, and PCB layouts were developed, laying the groundwork for future hardware implementation.

Acknowledgments

We express our gratitude to our project supervisor, Dr. Sam Darshi, for providing guidance and motivation of the project. We also thank our Department's Technical Supt. Kamaljeet Singh for assisting with component availability and PCB designing queries. We also acknowledge our team's dedication to overcoming challenges through independent study and simulation-based design.

Contents

1 Introduction

1.1 Problem Statement

Underwater communication is vital for marine research, underwater robotics, environmental monitoring, and military applications. Unlike terrestrial communication, which uses electromagnetic waves, underwater communication relies on acoustic signals due to the high attenuation of radio waves in water. However, acoustic communication faces significant challenges:

- **High Attenuation**: Sound waves in water experience greater attenuation than in air, particularly at higher frequencies, limiting communication range and bandwidth.
- **Weak Signals**: Hydrophones, which convert acoustic pressure waves into electrical signals, produce very low-amplitude signals ($\mu\mathrm{V} to \,\mathrm{mV}$) due to their high source impedance and the low intensity of underwater acoustic waves.
- **Noise Interference**: Underwater environments are noisy, with interference from natural sources (e.g., ocean currents, marine life) and anthropogenic sources (e.g., shipping, sonar), degrading signal quality.
- **Power Constraints**: Underwater systems often rely on battery power, necessitating high efficiency to extend operational life and minimize heat dissipation in sealed enclosures.

To address these challenges, a specialized acoustic amplifier is required to amplify weak hydrophone signals, filter out noise, and drive a transducer for signal transmission, all while maintaining power efficiency.

1.2 Need and Objectives

The acoustic amplifier is essential to enable reliable underwater communication. Hydrophones require a low-noise, high-gain preamplifier to amplify their weak signals without introducing noise. A band-pass filter is needed to reject out-of-band noise, ensuring the signal remains within the 10 Hz to 20 kHz range typical for underwater communication. Finally, a power amplifier must efficiently drive low-impedance transducers to transmit signals. This project addresses these needs by designing a system that enhances signal clarity, improves signal-to-noise ratio (SNR), and operates efficiently in the challenging underwater environment.
The project aims to achieve the following objectives:

1. Design a low-noise preamplifier using the TI JFE150 to amplify hydrophone signals while maintaining high input impedance and minimal noise.
2. Develop a 4th-order band-pass filter using the Sallen-Key topology to filter signals within the 10 Hz to 20 kHz range, rejecting DC offsets and high-frequency noise.
3. Create a power amplifier using the TI TPA3116D2 to efficiently drive the underwater transducer with sufficient power output.

4. Simulate the entire system using LTspice to verify performance and ensure design requirements are met.

5. Design a printed circuit board (PCB) following best practices for noise minimization, component placement, and environmental resilience for underwater use.

1.3 System Block Diagram and Component Order

The acoustic amplifier system is represented by the following block diagram:

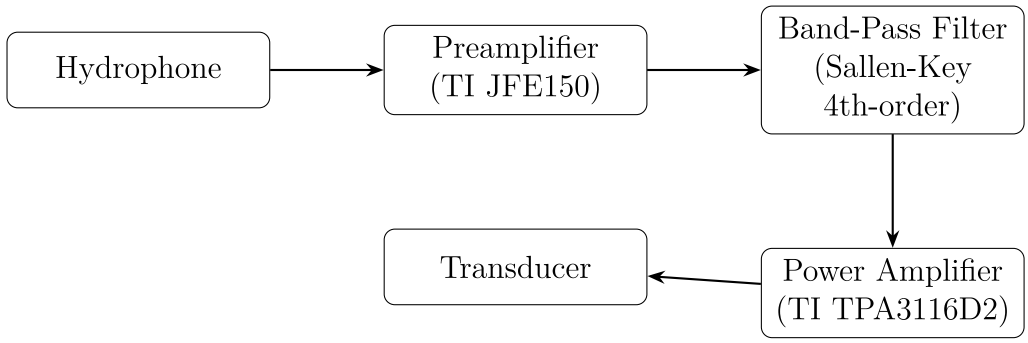

Figure 1: Block diagram of the acoustic amplifier system.

The system follows a specific order: Hydrophone → Preamplifier → Band-Pass Filter → Power Amplifier → Transducer. This sequence is critical for effective signal processing:

- **Preamplifier First**: The hydrophone produces weak signals (microvolts to millivolts) that must be amplified immediately to prevent loss due to attenuation or noise. The TI JFE150 preamplifier provides high gain (60 dB) and low noise, ensuring the signal is strong enough for further processing.

- **Filter Second**: After amplification, the signal contains amplified noise and unwanted frequencies. The Sallen-Key 4th-order band-pass filter removes DC offsets (below 10 Hz) and high-frequency noise (above 20 kHz), preserving the 10 Hz to 20 kHz range and improving SNR.

- **Power Amplifier Last**: The filtered signal requires significant power to drive the transducer, which has a low impedance (4–32 Ω). The TI TPA3116D2 power amplifier delivers up to 50 W with high efficiency (>92%), suitable for battery-powered underwater systems.

Placing the filter before the preamplifier is impractical because:

- The weak hydrophone signal would be further attenuated by the filter, reducing its amplitude and making amplification more challenging.

- The high-impedance nature of the hydrophone signal makes it susceptible to noise pickup before amplification, degrading signal quality.

Thus, amplification must precede filtering to ensure the signal is robust enough for processing.

2 Literature Review

The design of the acoustic amplifier is informed by technical literature, including application notes from Texas Instruments and industry practices for underwater acoustics and analog circuit design. This section reviews the theoretical foundations and commercially available components for each stage of the system.

2.1 Preamplifier: TI JFE150

Theory and Design: The TI JFE150 is a discrete junction field-effect transistor (JFET) designed for ultra-low-noise amplification of small signals from high-impedance sensors, such as hydrophones. According to the TI application note (1), which was also verified by us in LTspice using the same components, the JFE150 offers:

- **High Input Impedance**: Prevents loading of high-impedance hydrophones, ensuring signal integrity.
- **Low Noise**: Input-referred noise of 1.99 nV/$\sqrt{\text{Hz}}$ at 10 Hz and 1.18 nV/$\sqrt{\text{Hz}}$ at 1 kHz, critical for amplifying weak signals in noisy underwater environments.
- **High Gain**: Closed-loop gain of 60 dB (1001 V/V) with a feedforward gain up to 83.92 dB, suitable for microvolt-level signals.
- **Frequency Response**: Flat from 16 Hz to 43 kHz, covering the underwater communication band (10 Hz to 20 kHz).
- **Stability**: A phase margin of 87.4° ensures stable operation, with a feedback network (resistors RF2, RS1, RS2, and capacitor CS) maintaining consistent gain despite JFET transconductance variations.

The JFE150 is paired with an op-amp (e.g., OPA202) to form a low-noise preamplifier, addressing the limitations of bipolar op-amps, which have high input bias currents unsuitable for high-impedance sensors.

Why Chosen: The JFE150's ultra-low noise and high input impedance make it ideal for hydrophones, which produce weak signals in noisy underwater conditions. Its flexible biasing and wide frequency response ensure compatibility with underwater communication requirements.

Commercially Available Alternatives:

- **Benthowave Hydrophone Preamplifiers** (`https://www.benthowave.com/products/preamplifier.html`): Specialized for underwater applications, offering low noise and high gain tailored for hydrophones.
- **Analog Devices AD797**: A low-noise op-amp with high input impedance, suitable for sensor applications but less specialized than the JFE150.
- **TI OPA827**: A low-noise, rail-to-rail op-amp, effective for general-purpose amplification but not optimized for high-impedance sensors.

2.2 Filter: Sallen-Key 4th-Order Band-Pass

Theory and Design: The band-pass filter rejects DC offsets and high-frequency noise, preserving the dynamic range for the 10 Hz to 20 kHz band. The Sallen-Key topology, as described in (2), is used for its simplicity and ease of cascading. The filter comprises:

- **High-Pass Stage**: A 2nd-order filter with a cutoff frequency of ≈20 Hz, implemented using equal resistors (R1 = R2 = 82 kΩ) and capacitors (C1 = C2 = 0.1 μF).
- **Low-Pass Stages**: Two cascaded 2nd-order filters with a cutoff frequency of ≈30 kHz, using equal resistors (R1 = R2 = 51 Ω) and capacitors (C1 = C2 = 0.1 uF).

The filter achieves a 4th-order Butterworth response for a flat passband and sharp roll-off. Op-amps like TI OPA2836 or Analog Devices ADA4528 provide low noise and rail-to-rail operation.

Why Chosen: The Sallen-Key topology is simple, requires fewer components than alternatives like Multiple-Feedback (MFB), and supports easy cascading for higher-order filters. The band-pass design ensures optimal SNR by focusing on the desired frequency range.

Commercially Available Alternatives:

- **Active Filter ICs**: Integrated circuits like TI UAF42 provide configurable active filters but are less flexible for custom underwater frequency ranges.
- **Discrete Sallen-Key Filters**: Common in audio systems, using op-amps like OPA2134 for low-noise performance.
- **Digital Signal Processors (DSPs)**: Offer programmable filtering but are more complex and power-intensive, less suitable for battery-powered underwater systems.

2.3 Power Amplifier: TI TPA3116D2

Theory and Design: The power amplifier drives low-impedance transducers (4–32 Ω) with sufficient power (up to 50 W). The TI TPA3116D2, a Class-D switching amplifier, is selected for its high efficiency (>92%) and compact size (3). Key features include:

- **Efficiency**: Up to 92%, reducing heat dissipation in sealed underwater enclosures.
- **Power Output**: Up to 50 W into a 4 Ω load, suitable for piezoelectric transducers.
- **Low Distortion**: THD+N of 0.1% at 1 W, 1 kHz, ensuring clean signal reproduction.
- **Output Filter**: An LC filter (L1 = L2 = 10 μH, C1 = C2 = 0.68uF) suppresses switching noise.

The amplifier operates on a 4.5 V to 26 V supply (recommended 24 V NiMH battery) and is configured for a 32 dB gain.

Why Chosen: Class-D amplifiers like the TPA3116D2 are more efficient than Class-AB alternatives, critical for battery-powered underwater systems. Its compact design and low THD+N make it suitable for harsh underwater conditions.

Commercially Available Alternatives:

- **TI TPA3130D2**: Similar to TPA3116D2, with slightly higher efficiency and suitability for depths up to 50 m.
- **ETEC PA1001**: Hermetically sealed for depths >100 m, ideal for deep-sea applications.
- **TI OPA541 (Class-AB)**: Less efficient but simpler, suitable for applications where efficiency is less critical.

3 System Design

The acoustic amplifier system is designed to process hydrophone signals through three stages: preamplification, filtering, and power amplification. Each stage is optimized for underwater communication requirements.

3.1 Preamplifier: TI JFE150

The preamplifier uses the TI JFE150 JFET in a common-source configuration, paired with an OPA202 op-amp for additional gain. The circuit is designed as follows:

- **Biasing**: Resistors RS1, RS2, and capacitor CS set the JFET's operating point, with a transconductance gain ($g_m = 15.7\,\text{mS}$).
- **Feedback Network**: Resistor RF2 (1 MΩ) and feedback components achieve a closed-loop gain of 60 dB.
- **Frequency Response**: Flat from 16 Hz to 43 kHz, covering the underwater communication band.
- **Stability**: Phase margin of 87.4° ensures stable operation.

Component Values: **Simulation Results**: LTspice simulations confirm a 60 dB

Table 1: Preamplifier Component Values

Component	Value
JFE150	Ultra-low-noise JFET
OPA202	Low-noise op-amp
RF2	10 kΩ
RS1, RS2	280, 10Ω
CS	1 mF

gain from 16 Hz to 43 kHz, with noise levels of 1.99 nV/$\sqrt{\text{Hz}}$ at 10 Hz and 1.18 nV/$\sqrt{\text{Hz}}$ at 1 kHz, matching TI's specifications (1).

3.2 Filter: Sallen-Key 4th-Order Band-Pass

The filter is a 4th-order band-pass design using Sallen-Key topology, comprising:

- **High-Pass Stage**: 2nd-order, $f_c \approx 10.3\,\mathrm{Hz}$, with R1 = R2 = 33 kΩ, C1 = C2 = 0.47 μF, and op-amp gain of 1.6 (R3 = 10 kΩ, R4 = 6.2 kΩ) for a Butterworth response (Q = 0.707).
- **Low-Pass Stages**: Two cascaded 2nd-order filters, $f_c \approx 19.4\,\mathrm{kHz}$, with R1 = R2 = 8.2 kΩ, C1 = C2 = 1.0 nF, and identical op-amp gain.

Component Values:

Table 2: Filter Component Values

Stage	Component	Value
High-Pass	R1, R2	82kΩ
	C1, C2	0.1μF
	R3	open
	R4	short
Low-Pass (x2)	R1, R2	51 Ω
	C1, C2	0.1u F
	R3	open
	R4	short

Op-Amps: TI TL072 or Analog Devices ADA4528, selected for low noise and rail-to-rail performance.

3.3 Power Amplifier: TI TPA3116D2

The power amplifier uses the TI TPA3116D2 Class-D amplifier, configured as follows:

- **Gain**: 32 dB, set by R1 = 39kΩ and R2 ≈ 100kΩ.
- **Output Filter**: LC filter with L1 = L2 = 10 μH, C1 = C2=0.68uF
- **Load Stability**: A series resistor (0.5–1 Ω) ensures stability with capacitive transducers.
- **Power Supply**: 24 V NiMH battery, compatible with the 4.5 V to 26 V range.

Component Values:

Table 3: Power Amplifier Component Values

Component	Value
TPA3116D2	Class-D amplifier
R1	20 kΩ
R2	100 kΩ
L1, L2	10 μH
C1, C2	0.68uF

4 Simulation Results

LTspice simulations validate the design:

- **Preamplifier**: The JFE150 circuit shows a 60 dB gain from 16 Hz to 43 kHz and noise levels of 1.99 nV/$\sqrt{\text{Hz}}$ at 10 Hz and 1.18 nV/$\sqrt{\text{Hz}}$ at 1 kHz, matching (1).

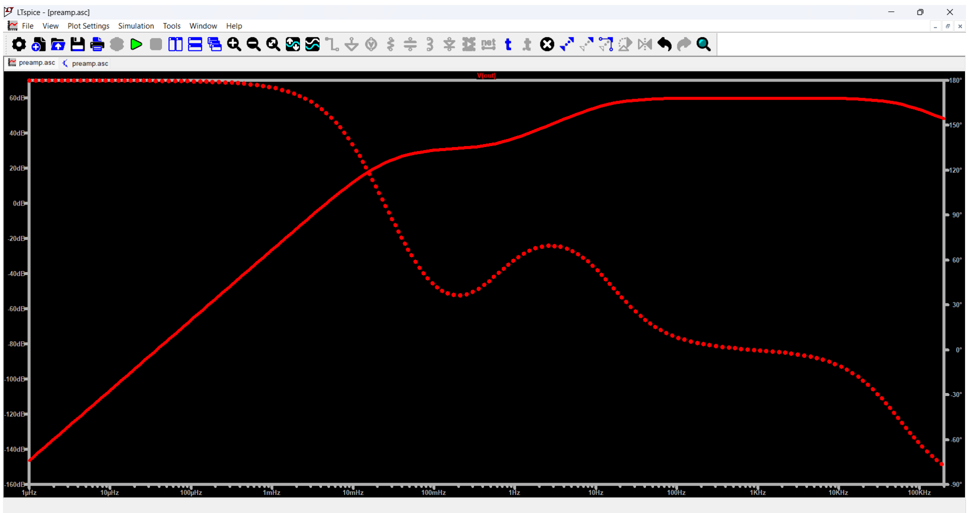

Figure 2: Preamplifier gain vs. frequency from LTspice.

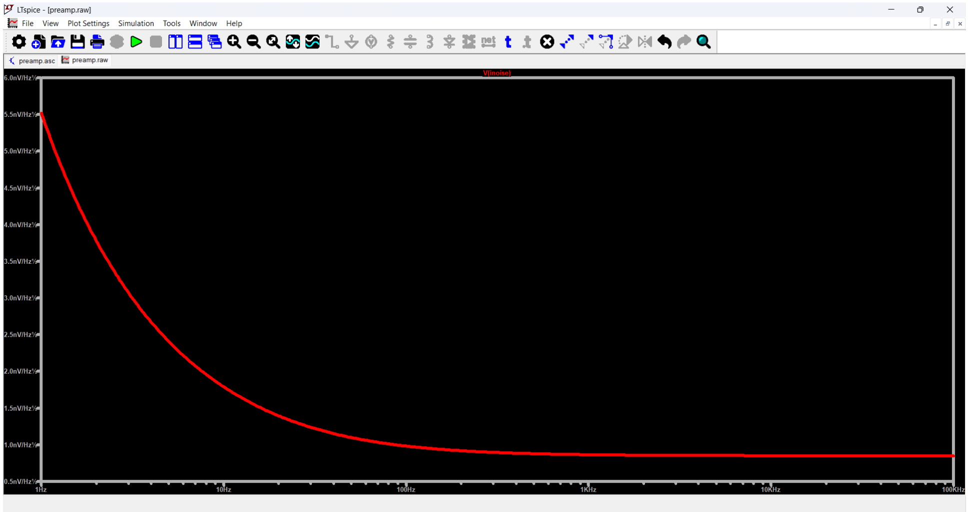

Figure 3: Input Referred Noise Analysis Simulation

5 PCB Design

The PCB was designed using EasyEDA, following best practices:

- **Preamplifier**: Short signal paths and a solid ground plane minimize noise.
- **Filter**: Low-ESR capacitors and metal-film resistors are used. Op-amps are decoupled with 0.1 μF and 10 μF capacitors.
- **Power Amplifier**: The TPA3116D2 layout includes a star-connected ground and an LC filter near the output.

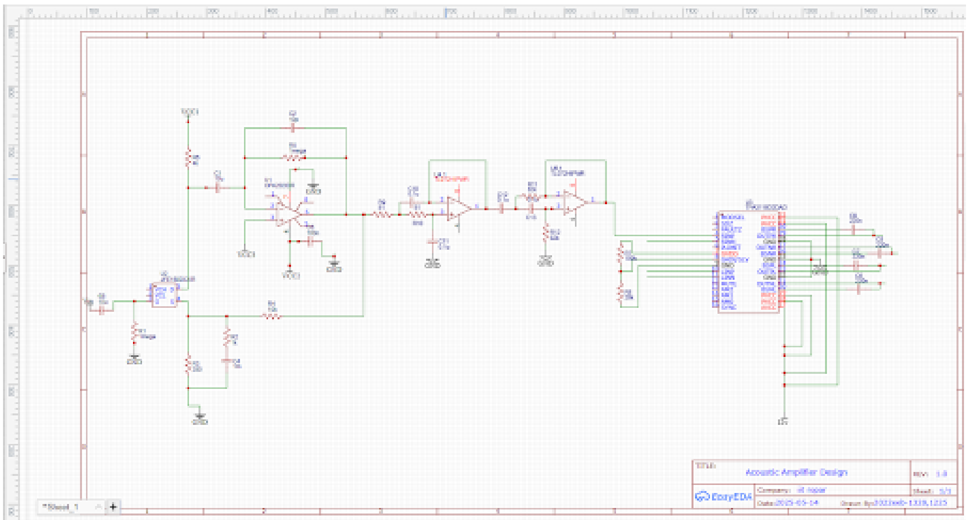

Figure 4: Schematic of overall acoustic amplifier.

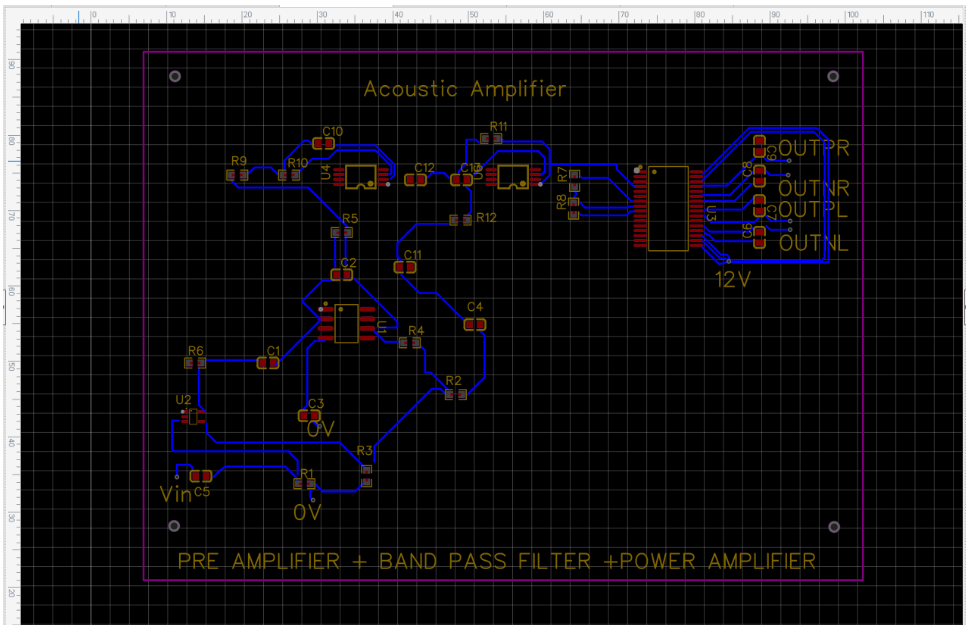

Figure 5: PCB layout for the acoustic amplifier.

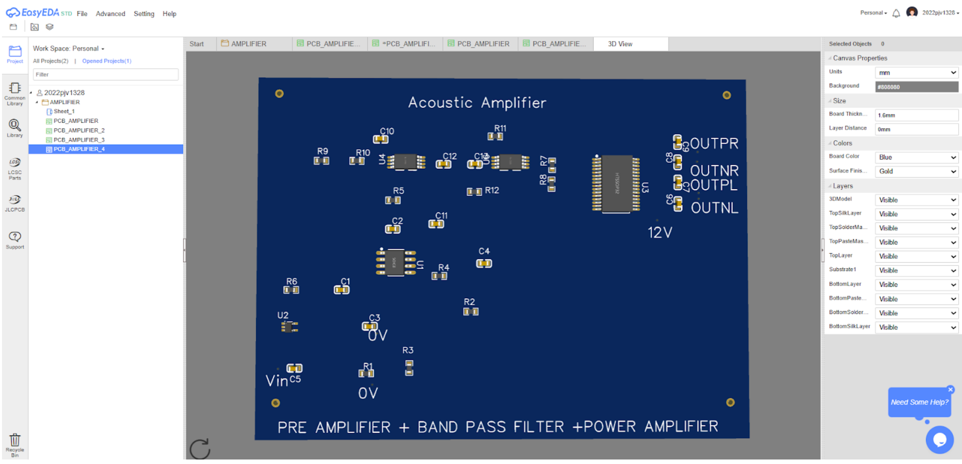

Figure 6: Final 3D layout for the acoustic amplifier.

6 Challenges and Limitations

Component unavailability prevented breadboard prototyping, shifting focus to simulations and PCB design. This limited hardware validation but ensured a robust theoretical foundation. Future work includes sourcing components and testing the PCB.

7 Conclusion and Future Work

The project designed an acoustic amplifier using the TI JFE150 preamplifier, Sallen-Key 4th-order bandpass filter, and TI TPA3116D2 power amplifier. LTspice simulations confirm performance, and PCB layouts are ready for fabrication. Future steps include hardware prototyping, underwater testing, and impedance matching optimization.

References

[1] Texas Instruments, *JFE150 Ultra-Low-Noise Pre-Amp*, SLPM015, October 2021.
`https://www.ti.com/lit/an/slpa018/slpa018.pdf`

[2] George Washington University, *Active Filter Design Techniques*, Department of Electrical and Computer Engineering.
`https://www2.seas.gwu.edu/~ece121/Spring-11/filterdesign.pdf`

[3] Texas Instruments, *TPA3116D2 50-W Stereo Class-D Audio Amplifier*, Datasheet, Revised July 2016.
`https://www.ti.com/lit/ds/symlink/tpa3116d2.pdf`