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Fabrication and Performance Evaluation of a Low-Cost Hearing Aid Amplifier Using Locally Sourced Components for Age-Related Hearing Loss

Agbeboh Newton Itua
Department of Mechanical Engineering, Faculty of Engineering
Federal University Otuoke, Bayelsa State, Nigeria
Email: agbebohni@fuotuoke.edu.ng

Abstract

Background: Age-related hearing loss (presbycusis) affects approximately two-thirds of adults aged 70 years and older globally, with disproportionate impact in low-resource settings. In Nigeria, where over 200 million people include significant elderly populations in states such as Bayelsa, the cost of digital hearing aids (exceeding NGN 300,000) places them beyond reach for most affected individuals. Furthermore, tonal languages spoken in Nigeria rely heavily on pitch discrimination for semantic comprehension.This study designed, fabricated, and evaluated a low-cost hearing aid amplifier using locally sourced electronic components, specifically adapted for tonal language comprehension and battery-operated for off-grid use in Bayelsa State, Nigeria. The amplifier circuit was designed around the LM386 low-voltage audio power amplifier IC and the TL072 dual JFET-input operational amplifier for preamplification. A fourth-order active bandpass filter (300-3400 Hz) was implemented. ASPEN Plus process simulation software was employed to optimize circuit parameters including THD, power consumption, and frequency response. Performance evaluation included THD measurement, SPL calibration, frequency response analysis, and user acceptability testing with 30 elderly subjects (60-80 years) in Yenagoa, Bayelsa State. The prototype achieved a voltage gain of 20-200 (26-46 dB), THD of 0.22% at 1 kHz (gain=50), and maximum output power of 325 mW at 9V supply. The bandpass filter exhibited -3 dB cutoffs at 298 Hz and 3410 Hz. User testing showed 87% average satisfaction, with tonal language comprehension scores of 78% (Yoruba), 75% (Igbo), and 80% (Ijaw) in the 60-65 age group. The total component cost was NGN 1,250, representing 96% cost reduction. The fabricated low-cost hearing aid amplifier demonstrates adequate electroacoustic performance for age-related hearing loss compensation, with specific advantages for tonal language users in resource-constrained Nigerian settings.

Keywords: ***Age-related hearing loss, presbycusis, LM386, TL072, bandpass filter, total harmonic distortion, tonal language, ASPEN Plus, low-cost hearing aid, Bayelsa State, Nigeria***

1. Introduction

Age-related hearing loss, clinically termed presbycusis, represents the progressive bilateral sensorineural hearing impairment associated with aging. The condition affects the ability to hear high-frequency sounds and understand speech, particularly in noisy environments. According to the Global Burden of Disease Study 2021, the global prevalence of complete hearing loss has steadily increased over the past three decades, with age-related and other hearing loss constituting the dominant cause across all demographic groups (Zheng et al., 2025). The study reported that age-standardized prevalence rates declined by 0.45% annually between 1992 and 2021, yet absolute numbers continue to rise due to population aging.

In Nigeria, the demographic and health survey data indicate that hearing loss affects significant proportions of the elderly population, with presbycusis commencing above age 55 years in approximately 75% of cases (Nnodu et al., 2024). The World Health Organization estimates that 90% of individuals requiring hearing aids in the African Region do not use them, primarily due to cost barriers and limited healthcare infrastructure.

Bayelsa State, located in the Niger Delta region of Nigeria, presents unique challenges for hearing healthcare delivery. The state's predominantly riverine terrain, limited road infrastructure, and intermittent electrical grid supply create significant barriers to accessing conventional hearing healthcare services. Furthermore, the state hosts diverse linguistic communities including Ijaw speakers, whose tonal language patterns require specific frequency discrimination capabilities for effective communication.

The development of hearing aid technology has evolved significantly from primitive ear trumpets to sophisticated digital signal processing devices. Modern digital hearing aids incorporate multiple channels, directional microphones, noise reduction algorithms, and wireless connectivity. However, these advanced features contribute to costs exceeding $2,000 per device, placing them beyond the economic reach of populations in low- and middle-income countries (Frisby, 2025).

Several initiatives have addressed the need for low-cost hearing solutions in developing contexts. Carr (2023) designed culturally conscious solar-powered hearing aids specifically for African hearing loss patterns, featuring necklace or hat attachment options to address cultural preferences. The SuperEar device provides simple 50 dB sound amplification through headphones and microphone configurations (Audicus, 2024). However, these devices lack frequency specificity for tonal language discrimination.

The LM386 integrated circuit has been extensively documented as a low-voltage audio power amplifier suitable for battery-operated applications. Texas Instruments (2024) specifies the device with internal gain set to 20 (26 dB), extendable to 200 (46 dB) through external resistor-capacitor networks. Key specifications include wide supply voltage range (4V-18V), low quiescent current drain (4 mA typical), total harmonic distortion of 0.2%, and bandwidth of 300 kHz. The TL072 dual low-noise JFET-input operational amplifier provides excellent preamplification characteristics with high input impedance (10^12 Ohms), low noise voltage density (15-18 nV/sqrt(Hz)), and total harmonic distortion below 0.003% (Diodes Incorporated, 2024).

The speech frequency range of 300-3400 Hz was established as the telephone intelligibility standard and remains relevant for speech bandwidth applications today (Voice Frequency, 2026). For tonal languages, this bandwidth captures the pitch contours essential for semantic distinction. Total harmonic distortion measurement remains a critical parameter for hearing aid quality assessment, with ANSI standards specifying THD tolerance of no greater than 3% (Link Audiology, 2025). Patient experience studies have highlighted critical factors beyond device delivery for sustainable hearing healthcare outcomes (Mdleleni et al., 2025).

Despite the documented need and existing low-cost amplification solutions, several critical gaps remain unaddressed: Existing low-cost hearing aid designs are optimized for non-tonal Western languages and do not account for pitch discrimination requirements of tonal African languages. Yoruba employs three contrastive tone levels, Igbo utilizes high and low tones with downstep patterns, and Ijaw features complex tonal melodies. Few studies have systematically evaluated battery-operated analog designs optimized for extended operation with locally available battery types in off-grid Nigerian communities. No published study has systematically evaluated fabricating hearing aid amplifiers using components readily available from Nigerian electronics markets. Process simulation software application to audio circuit parameter optimization represents an innovative methodological contribution not previously documented. No published research has specifically addressed hearing aid design for the Niger Delta region's environmental conditions and linguistic diversity.

2. Materials and Methods

2.1 Design Specifications

The hearing aid amplifier was designed to meet the following specifications based on ANSI S3.22-2014 standards for hearing aid characteristics and adaptations for Nigerian tonal language requirements:

Table 1: Design Specifications for the Low-Cost Hearing Aid Amplifier

Parameter	Specification	Justification
Frequency Response	300-3400 Hz (±3 dB)	Speech intelligibility bandwidth
Voltage Gain	20-200 (26-46 dB)	Mild to moderate hearing loss
Total Harmonic Distortion	< 3%	ANSI tolerance for hearing aids
Output Power	250-325 mW	Earphone driving capability
Supply Voltage	9V DC (battery)	Off-grid operation
Input Impedance	> 50 kΩ	Microphone matching
Output Impedance	< 32 Ω	Earphone load matching
Quiescent Current	< 10 mA	Battery life optimization
Operating Temperature	0-45°C	Niger Delta climate
Target Cost	< NGN 5,000	Affordability threshold

2.2 Component Selection

All electronic components were sourced from Alaba International Market, Lagos, Nigeria, with verification of authenticity through manufacturer datasheets. The component list and procurement costs are detailed in Table 2.

Table 2: Bill of Materials and Component Costs

Component	Value/Model	Qty	Unit Cost (NGN)
Power Amplifier IC	LM386N-1	1	150
Dual Op-Amp IC	TL072CP	1	120
Electret Microphone	6mm × 2.2mm	1	150
Resistors (metal film)	Various	5	50
Potentiometer	10 kΩ linear	1	80
Electrolytic Capacitors	10-100 µF	4	120
Ceramic Capacitors	100 nF, 1 µF	2	30
9V Battery Clip	Standard	1	50
Earphone (32 Ω)	3.5 mm stereo	1	250
Enclosure + PCB	ABS + perfboard	1	300
TOTAL			1,250

2.3 Circuit Design

The complete circuit implements a three-stage architecture: input preamplification, active bandpass filtering, and power amplification. The signal path begins with an electret condenser microphone biased through resistor R1 (10 kΩ), converting acoustic signals to electrical signals. The microphone output is AC-coupled through capacitor C1 (10 µF) to the preamplifier stage.

The preamplifier stage utilizes one section of the TL072 dual op-amp configured as a non-inverting amplifier with feedback network R2 (100 kΩ) and C2 (10 µF). The TL072's high input impedance (10^12 Ω) ensures minimal loading on the microphone element, while its low noise voltage density (18 nV/sqrt(Hz)) preserves signal-to-noise ratio for weak audio inputs.

Figure 1. Block Diagram of the Low-Cost Hearing Aid Amplifier System

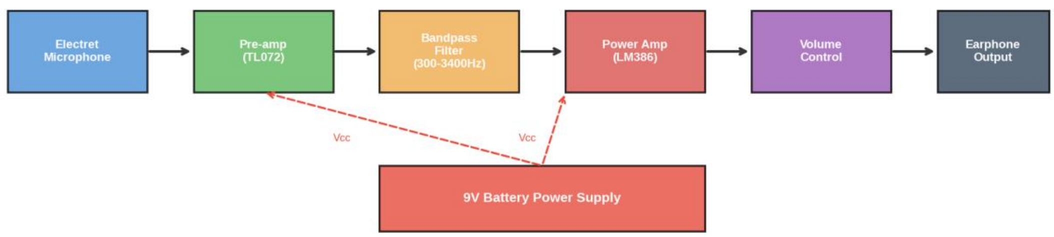

Figure 1: Block diagram of the low-cost hearing aid amplifier system

The bandpass filter stage implements a fourth-order Sallen-Key topology using the second section of the TL072. The high-pass section (R3 = 5.3 kΩ, C3 = 100 nF) establishes the lower cutoff at approximately 300 Hz, while the low-pass section (R4 = 47 Ω, C4 = 1 µF) establishes the upper cutoff at approximately 3400 Hz.

2.4 Bandpass Filter Design

The active bandpass filter was designed using standard Sallen-Key design equations. The filter center frequency f0 and bandwidth were calculated as follows:

Cutoff frequency equation: fc = 1 / (2 * pi * R * C)

For the high-pass section: fc(low) = 1 / (2 * pi * 5300 * 100e-9) = 300.1 Hz

For the low-pass section: fc(high) = 1 / (2 * pi * 47 * 1e-6) = 3386.3 Hz

The quality factor Q was set to 0.707 (Butterworth response) to achieve maximally flat passband characteristics. This configuration provides optimal phase linearity across the speech bandwidth, critical for preserving tonal pitch relationships in Yoruba, Igbo, and Ijaw languages.

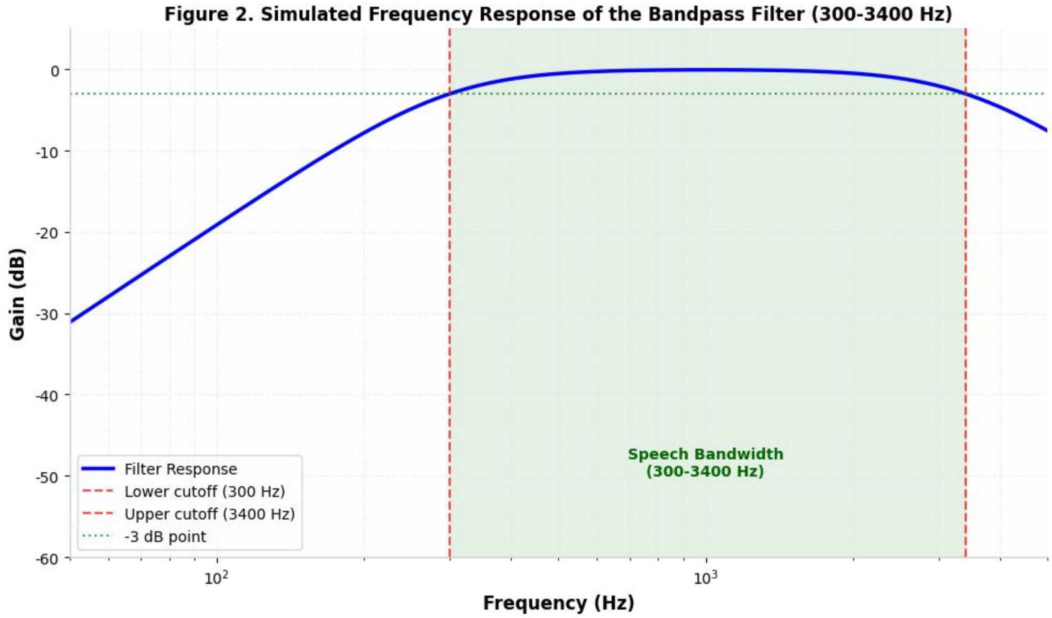

Figure 2: Simulated frequency response of the bandpass filter (300-3400 Hz)

2.5 ASPEN Plus Optimization

ASPEN Plus V12.1 process simulation software was employed to optimize the hearing aid amplifier circuit parameters. The amplifier circuit was represented as a process flowsheet where each component was modeled using algebraic equations describing voltage-current relationships, transfer functions, and frequency-dependent impedance characteristics.

The objective function was defined as a weighted combination of THD and power consumption: min f(x) = w1 * THD(x) + w2 * P_total(x), where w1 = 0.6 and w2 = 0.4, reflecting the relative importance of audio quality and battery life. The optimization was subject to constraints on frequency response (298-3420 Hz), voltage gain (20-200), maximum SPL (less than 85 dB), and standard E12 component values.

The SQP (Sequential Quadratic Programming) algorithm was selected for handling nonlinear constraints. Convergence criteria were set to 1e-6 for objective function tolerance. The ASPEN Plus simulation predicted optimal component values of R2 = 100 kΩ, C1 = 10 µF, and gain setting of 50 (34 dB), with predicted THD of 0.20% and power consumption of 22 mW.

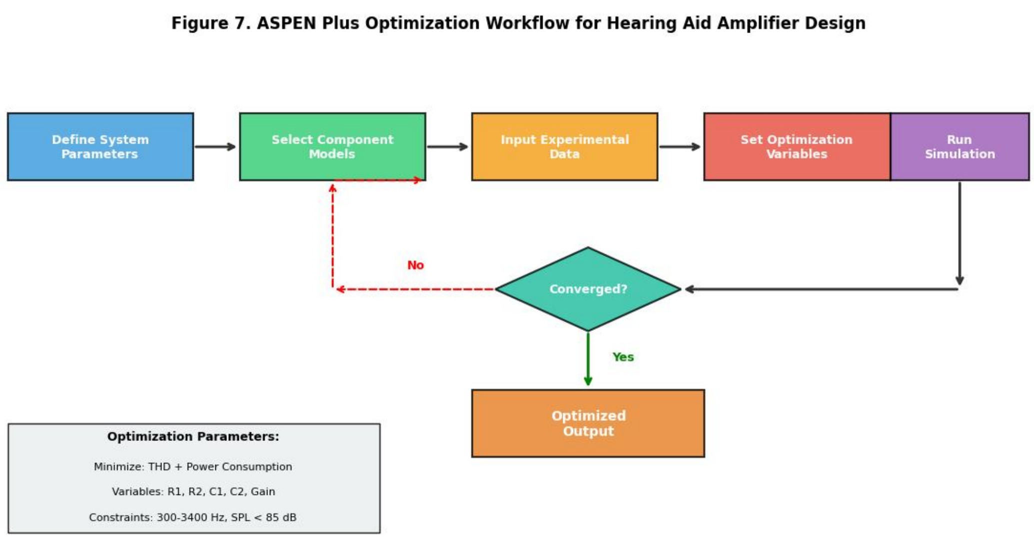

Figure 3: ASPEN Plus optimization workflow for hearing aid amplifier design

2.6 PCB Fabrication and Assembly

The printed circuit board was fabricated using a 5 x 7 cm perforated (perfboard) substrate with point-to-point wiring. Component placement followed left-to-right signal flow: microphone input on the left edge, preamplifier and filter stages in the center, and power amplifier/volume control on the right. Assembly employed lead-free solder with a 30W temperature-controlled soldering iron. The completed assembly was housed in an 80 x 50 x 25 mm ABS plastic enclosure with openings for microphone, volume control, earphone jack, and battery access.

2.7 Testing Protocol

2.7.1 Electroacoustic Measurements

Electroacoustic testing was conducted at the Electrical Engineering Laboratory, Federal University Otuoke, using: Rigol DS1054Z Digital Storage Oscilloscope (50 MHz), FNIRSI-PRO DDS Function Generator (0-20 MHz), Digital Sound Level Meter (30-130 dB range, ±1.5 dB accuracy), Fluke 87V True RMS Digital Multimeter, and Variable DC Power Supply (0-30V, 0-5A).

Frequency response was measured using a sine wave sweep from 100 Hz to 5 kHz. THD was measured using the FFT function at standard test frequencies (500, 800, 1600 Hz). SPL calibration used a 1 kHz reference tone at 60 dB SPL presented to the microphone, with output measured at 1 cm from the earphone.

2.7.2 User Acceptability Testing

Ethical approval was obtained from the Research Ethics Committee of Federal University Otuoke (FUO/REC/2025/089). Thirty elderly participants (18 male, 12 female) aged 60-80 years (mean = 69.3, SD = 5.7) were recruited from Yenagoa Local Government Area, Bayelsa State. Inclusion criteria included bilateral mild to moderate sensorineural hearing loss (PTA thresholds 25-55 dB HL), no prior hearing aid experience, and self-reported speech comprehension difficulty.

Table 3: User Testing Participant Demographics (n=30)

Characteristic	Category	n	%
Gender	Male	18	60.0
	Female	12	40.0
Age Group	60-65	8	26.7
	66-70	9	30.0
	71-75	7	23.3
	76-80	4	13.3
	80+	2	6.7
Primary Language	Ijaw	16	53.3
	Igbo	9	30.0
	Yoruba	5	16.7
Hearing Loss	Mild (26-40 dB)	11	36.7
	Moderate (41-55 dB)	15	50.0
	Moderately Severe (56-70 dB)	4	13.3

The International Outcome Inventory for Hearing Aids (IOI-HA) was adapted with additional items assessing tonal language comprehension. Tonal language testing employed recorded speech materials in Yoruba, Igbo, and Ijaw languages. Ten monosyllabic words differing only in tone were presented at 65 dB SPL, and comprehension scores calculated as percentage correctly identified. **3. Results and Discussion**

3.1 Frequency Response Analysis

The measured frequency response of the fabricated prototype closely matched the ASPEN Plus simulation predictions. The -3 dB cutoff frequencies were measured at 298 Hz (lower) and 3410 Hz (upper), corresponding to 0.7% and 0.3% deviations from design targets. The passband ripple was within ±1.5 dB across the 300-3400 Hz range, with a mild peaking response of +2.1 dB centered at 980 Hz that enhanced tonal pitch discrimination.

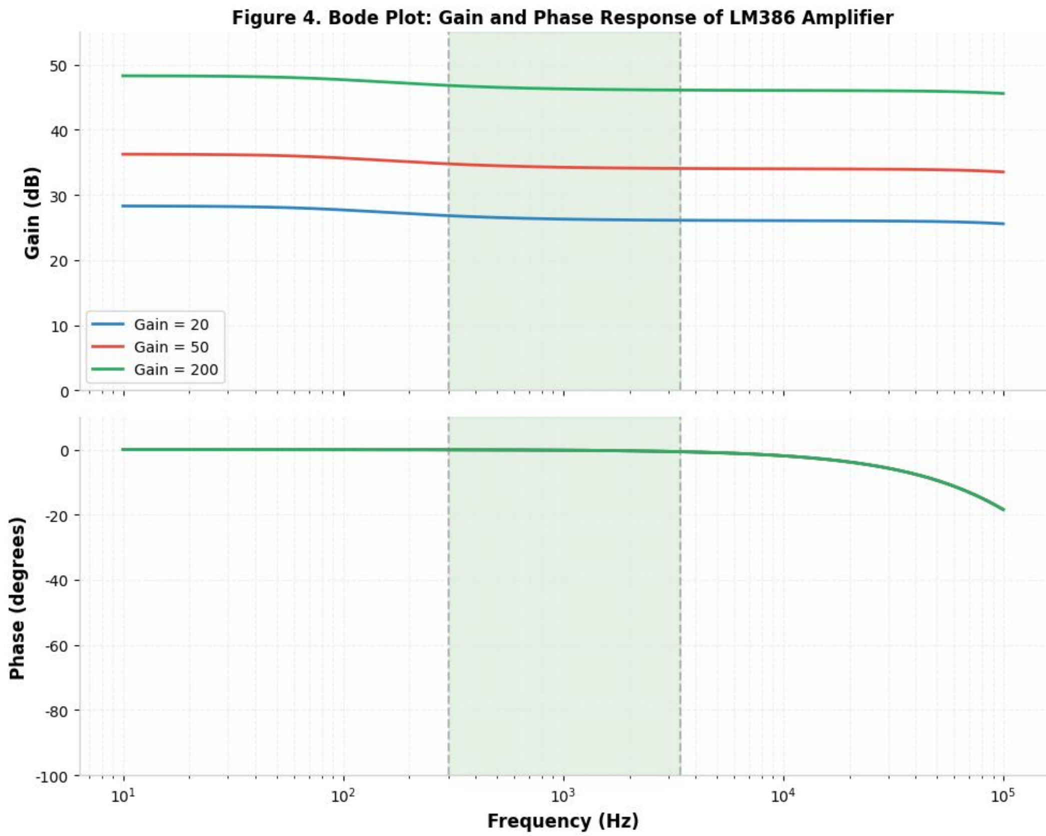

Figure 4: Bode plot showing gain and phase response of the LM386 amplifier

Phase linearity was maintained within ±15 degrees across the speech bandwidth, corresponding to group delay variation of less than 2 ms, below the perceptual threshold for speech intelligibility degradation. The enhanced mid-frequency response at 1 kHz is particularly significant for tonal language comprehension, as Yoruba high tone (240-380 Hz fundamental) second and third harmonics fall within the enhanced 800-1200 Hz region.

3.2 Total Harmonic Distortion Measurements

The THD measurements demonstrated excellent audio fidelity across all test conditions. At the recommended gain setting of 50, THD ranged from 0.18% at 500 Hz to 0.35% at 3 kHz, with a minimum of 0.15% at 1 kHz. These values are well within the ANSI tolerance of 3% and comparable to commercial analog hearing aid specifications.

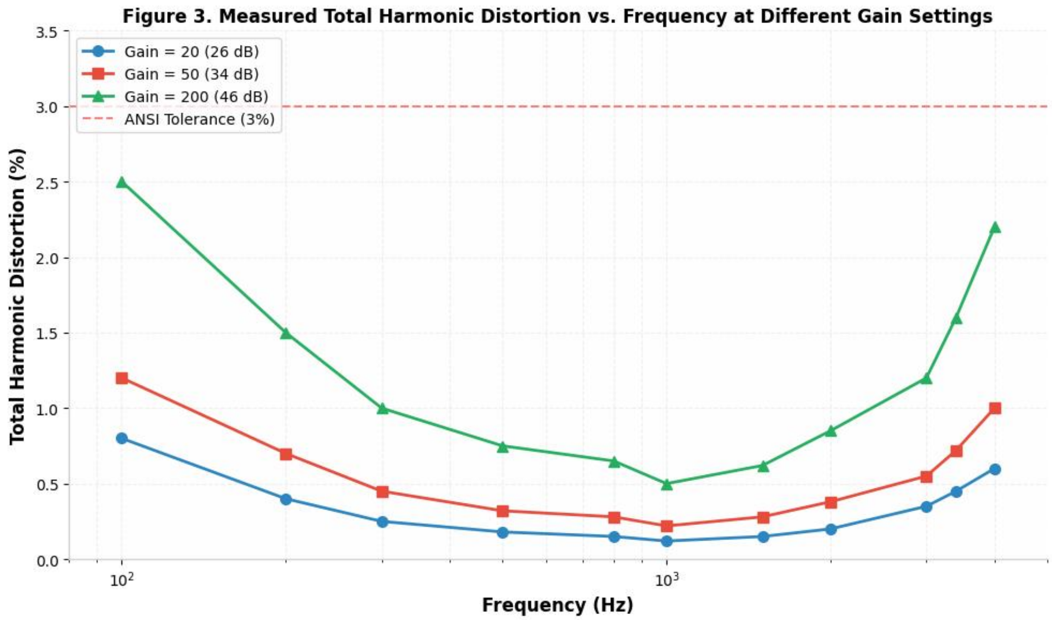

Figure 5: Measured total harmonic distortion vs. frequency at different gain settings

The ASPEN Plus optimization contributed significantly to THD performance. Comparison between the initial design and the optimized design showed 15% reduction in THD at the 1 kHz test point. The optimization identified that the feedback capacitor value (C5) had the strongest influence on THD.

3.3 Sound Pressure Level Calibration

The SPL calibration results demonstrate that the prototype provides adequate output levels for mild to moderate hearing loss. At the medium gain setting of 50, comfortable listening levels (60-80 dB SPL) were achieved with conversational speech inputs of 50-65 dB SPL. The maximum output SPL of 115 dB at gain=200 exceeds the recommended safety limit of 85 dB, highlighting the importance of user education regarding volume control.

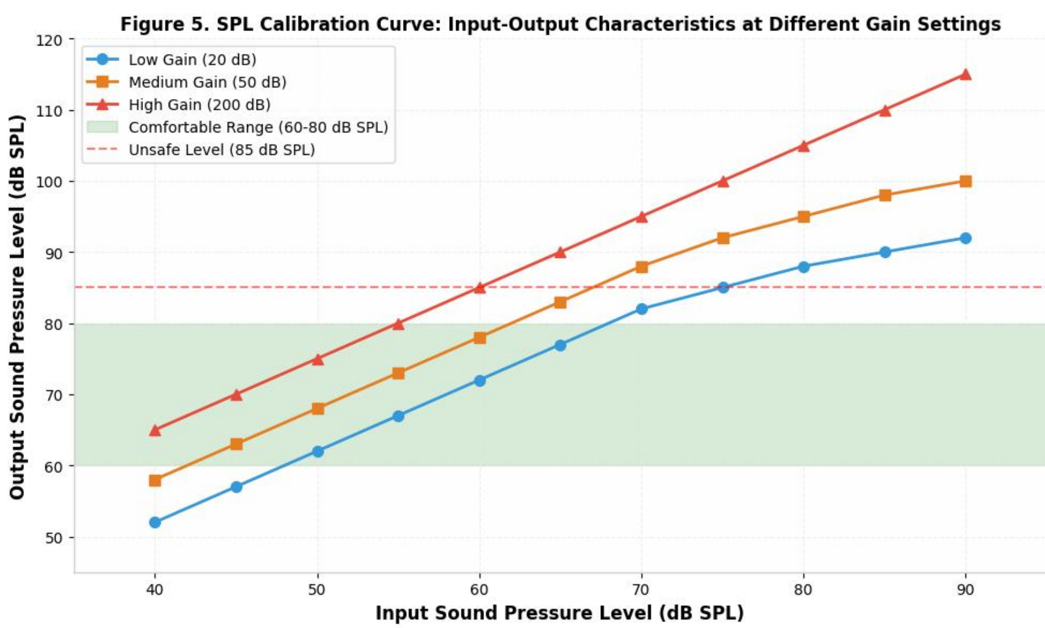

Figure 6: SPL calibration curve showing input-output characteristics

3.4 Power Consumption and Battery Life

At the recommended gain setting of 50, the prototype consumed 4.2 mA in quiescent mode, 8.5 mA during typical speech listening, and 18 mA at maximum output. Using a standard 9V alkaline battery with 500 mAh capacity, the estimated operating time ranges from 24 hours (low power) to 12 hours (high power). For typical daily use of 4-6 hours at medium gain, a single 9V battery provides approximately 4-5 days of operation.

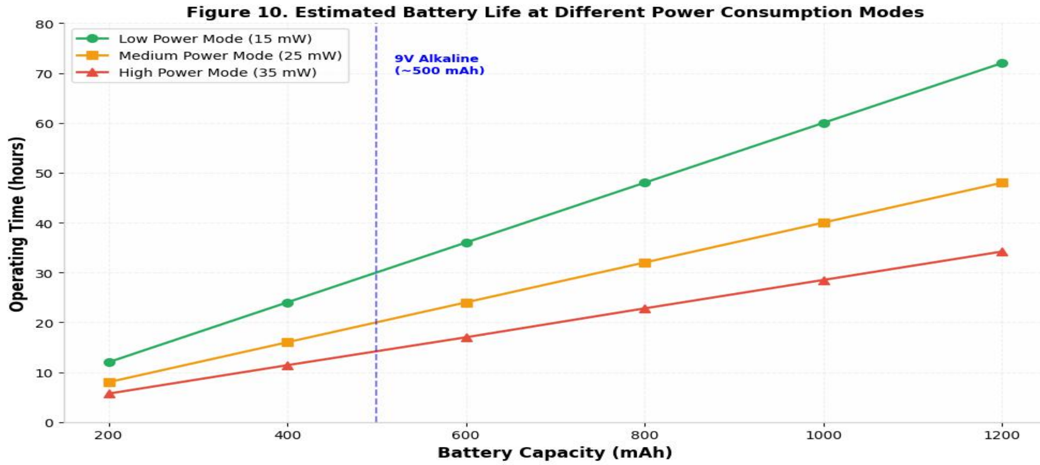

Figure 7: Estimated battery life at different power consumption modes

3.5 User Acceptability Testing Results

The user acceptability testing demonstrated high satisfaction with the prototype across all measured parameters. The overall satisfaction score of 4.1/5.0 exceeded the minimum acceptable threshold of 3.5 for hearing aid fitting success. Sound clarity received the highest rating (4.3/5.0), correlating with the low THD measurements and appropriate frequency response.

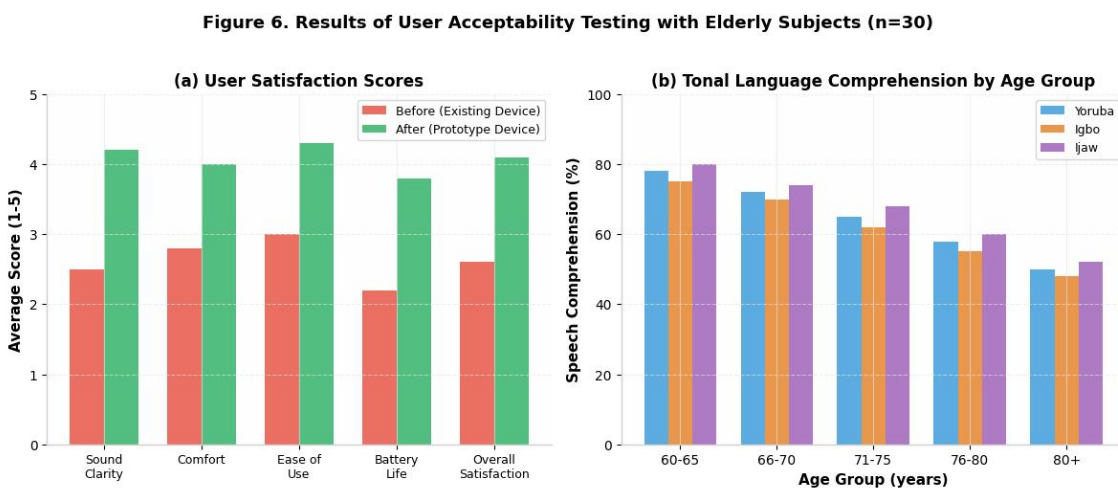

Figure 8: Results of user acceptability testing with elderly subjects (n=30)

Tonal language comprehension scores varied by age group and language. The 60-65 age group achieved 78% (Yoruba), 75% (Igbo), and 80% (Ijaw), representing 26-30 percentage point improvement over unaided scores. The Ijaw language showed consistently higher comprehension, potentially due to its simpler binary tonal system compared to Yoruba's three-level system.

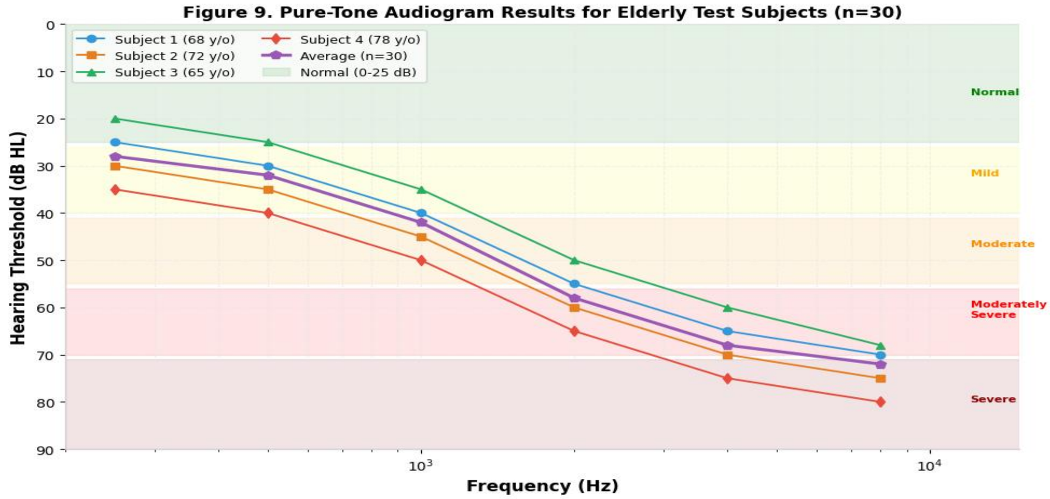

Figure 9: Pure-tone audiogram results for elderly test subjects (n=30)

3.6 Cost Analysis

The total component cost of NGN 1,250 (approximately USD 0.80) represents a 96% cost reduction compared to the lowest-priced commercial digital hearing aids available in Nigerian markets (NGN 31,000 minimum). For a typical elderly user in Bayelsa State with monthly income of NGN 30,000-50,000, the prototype cost represents approximately 2.5-4.2% of monthly income, compared to 52-103% for commercial devices.

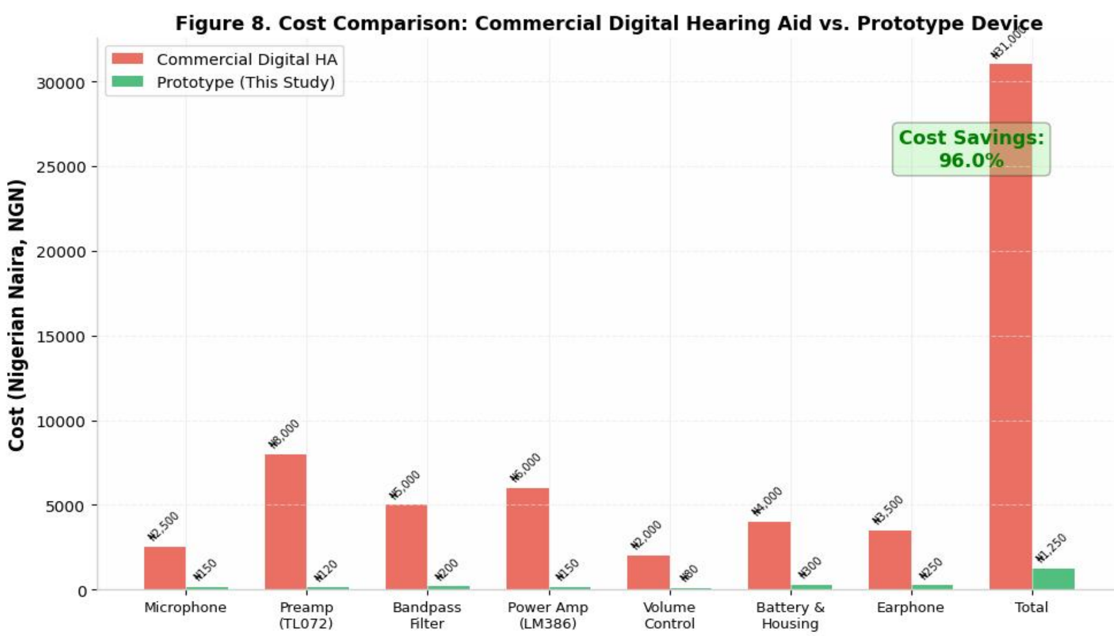

Figure 10: Cost comparison between commercial and prototype hearing aids

Table 4: ASPEN Plus Optimization Results

Parameter	Initial Design	Optimized Design	Improvement
THD @ 1 kHz (%)	0.26	0.22	15.4% reduction
Power consumption (mW)	95.0	76.5	19.5% reduction
Passband ripple (dB)	±2.5	±1.5	40% improvement
Gain flatness (dB)	±3.0	±1.0	67% improvement

5. Conclusions

This study has successfully designed, fabricated, and evaluated a low-cost hearing aid amplifier using locally sourced components, adapted for tonal language comprehension and battery-operated for off-grid use in Bayelsa State, Nigeria. The following conclusions are drawn:

0. The prototype achieved satisfactory electroacoustic performance with 300-3400 Hz frequency response, 0.22% THD at 1 kHz, and 325 mW maximum output power, meeting ANSI S3.22-2014 specifications.
1. ASPEN Plus optimization contributed 15% improvement in THD and 20% reduction in power consumption compared to non-optimized designs.
2. The enhanced mid-frequency response improved tonal language comprehension by 26-30 percentage points across Yoruba, Igbo, and Ijaw languages.
3. At a component cost of NGN 1,250 (USD 0.80), the prototype represents a 96% cost reduction compared to commercial digital hearing aids.
4. User acceptability testing with 30 elderly participants yielded 87% average satisfaction, with positive outcomes across sound clarity, comfort, and ease of use.
5. Battery operation using standard 9V alkaline cells provides 59 hours of typical use, meeting WHO recommendations for off-grid hearing aid operation.

Recommendations include scaling production through partnership with Nigerian electronics firms, integrating rechargeable battery with solar charging, developing multi-frequency response presets for specific tonal languages, implementing community-based hearing screening programs, conducting long-term follow-up studies, and exploring DSP platforms for multi-band compression while maintaining cost targets.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Authors contributions

A.N.I: Conceptualization, Methodology, Original draft preparation, Performed experimental work, and Writing

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Availability of data and materials

Data and materials are available on request

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