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Design, Analysis, and Implementation of a Frequency Modulation Receiver System with Enhanced Audio Power Amplification

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Abstract

This study designs an efficient frequency modulation (FM) receiver system aimed at accurately converting modulated signals into clear, discernible sounds. The system architecture integrates five core unit circuits: high-frequency amplification, mixer, local oscillator, discriminator, and audio power amplifier, with a focus on the design of the mixer and low-frequency power amplifier circuits. Utilizing mutilism and LTspice software, the mixer circuit was drawn and simulated, with results aligning with theoretical data, thus proving the feasibility of the design. In the audio power amplification section, the LM386 chip was chosen as the key component. After comparing various schemes and analyzing technical indicators such as output power, voltage gain, and bandwidth, the final design scheme was verified to not only meet the system design specifications but also satisfy the practical application needs of the system design.

Keywords

Communication Engineering; FM Receiver System; Mixer; Audio Power Amplifier Circuit; LM386 Chip.

1. Introduction

In the annals of wireless communication, frequency modulation (FM) stands out as a transformative technology that significantly enhanced the quality of radio broadcasting. By mitigating the noise and interference issues that were endemic to amplitude modulation (AM) systems, FM technology has enabled clearer and more reliable audio transmissions [1][2]. Central to the utilization of this technology is the FM receiver, a complex electronic device designed to demodulate frequency-modulated signals into audible sounds. The process involves several stages of signal processing, including amplification, mixing, demodulation, and audio amplification, each requiring precision engineering to ensure the integrity of the transmitted message.

The design of FM receiver systems is fraught with challenges, ranging from signal interference and frequency drift to the limitations imposed by the components used in their construction. Moreover, the modern demand for compact, energy-efficient, and cost-effective devices adds additional layers of complexity to their design and implementation. However, recent advancements in integrated circuits and digital signal processing have opened new avenues for overcoming these challenges, heralding a new era of sophisticated and reliable FM receivers [3].

This study is motivated by the continuous need for improvement in FM receiver technology, with a particular focus on the mixer and audio power amplifier circuits-key components that play pivotal roles in the frequency conversion process and in determining the final audio output quality, respectively [4]. The mixer circuit is essential for selecting and amplifying the desired FM signal from a broad spectrum of radio frequencies, while the audio power amplifier circuit enhances the

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demodulated signal to a level suitable for loudspeaker output. Through a detailed design and simulation approach, this paper aims to explore these components' design intricacies, employing state-of-the-art simulation tools to match the performance with high-quality sound output standards.

By setting out to achieve these goals, the present study seeks to make a substantial contribution to the field of FM receiver design. Through the optimization of key circuit components and the employment of modern simulation methodologies, it aims to enhance the performance and reliability of FM receivers, thereby supporting the advancement of wireless communication technologies.

2. Design and Operational Principles of a Frequency Modulation Receiver System

(1) Overview of System Architecture

The architecture of the frequency modulation (FM) receiver system plays a pivotal role in the effective transformation of modulated signals into audio outputs. This system is ingeniously crafted from a series of interconnected components, including a high-frequency amplifier, mixer, local oscillator, discriminator, audio power amplifier, and speaker. This integration facilitates the seamless conversion of received signals into audible sounds, ensuring the receiver's efficiency and reliability.

(2) Signal Amplification and Frequency Adjustment

At the heart of the FM receiver system lies the high-frequency amplification circuit, which initially magnifies the received low-frequency and weak signals. Following amplification, the mixer component adjusts the frequency of the FM signals, a crucial step that impacts the overall system performance. The local oscillator then plays a vital role by providing a stable frequency that aids in the precise tuning and selection of the desired signal.

(3) Intermediate Frequency Processing and Audio Output

Subsequent to frequency adjustment, the system employs an intermediate frequency (IF) strategy, where signals are mixed to a predetermined IF value. This process enhances the receiver's sensitivity and selectivity, thereby stabilizing its performance. The discriminator further demodulates the IF signal, extracting the original audio content. Finally, the audio power amplifier enriches the signal strength before it is conveyed to the speaker, culminating in the delivery of clear and discernible sound to the listener.

(4) System Specifications and Performance Metrics

As shown in Table 1, the FM receiver is designed to operate within a frequency range of 1.6-22 MHz, aligning with the transmitter's frequency spectrum. A notable feature of this system is its sensitivity, measured in terms of the minimal input signal voltage required for effective reception, which ranges from 10-25 µV. Additionally, the audio amplification circuit boasts an output power range of 0.25W to 1W, highlighting the system's ability to produce sound with sufficient volume and clarity under varying conditions.

Table 1. FM Receiver System Parameters

Parameter	Value
Transmission Frequency	10.7 MHz
Local Oscillator Frequency	10 MHz
Intermediate Frequency Signal	700 kHz
Target Audio Signal	2.778 kHz

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3. Design of the Mixer Circuit for FM Receiver

In the realm of frequency modulation (FM) receivers, the mixer circuit stands as a cornerstone, bridging the received signals with the desired frequency output through a process of frequency conversion. This chapter elucidates the design and operational nuances of the mixer circuit, underpinning the FM receiver's efficacy.

(1) Comparative Analysis and Selection of Mixer Designs

The quest for an optimal mixer circuit led to the evaluation of three distinct designs:

1) Transistor-Based Mixer Circuit: This design is revered for its simplicity and high frequency conversion gain. However, it demands a smaller amplitude of the local oscillator voltage, failing which, it succumbs to nonlinear distortion, severe interference, and increased noise levels.

2) Analog Multiplier Mixer Circuit: By essence, mixing is a linear translation of spectra, pivotal on acquiring the product of two input signals. Analog multipliers, serving as versatile nonlinear devices, facilitate the multiplication of analog signals, finding extensive applications in amplitude modulation, demodulation, and mixing.

3) Diode Mixer Circuit: Compared to its transistor and FET counterparts, the diode mixer circuit boasts lower noise, simplicity, fewer components, a broader dynamic range, better linearity, and higher operating frequencies. Despite lacking conversion gain, it's particularly suited for microwave frequency ranges where transistor mixers' conversion gain diminishes and noise figures escalate. Employing a diode mixer can effectively reduce the overall noise figure of the system.

After thorough analysis, a hybrid approach, amalgamating the first two designs, was adopted. This innovative mixer circuit integrates the transistor-based circuit within an analog multiplier framework, offering a simple circuitry with heightened frequency conversion gain, albeit with a caveat against large amplitude of the local oscillator signal to mitigate nonlinear distortions and noise.

(2) Mixer Circuit Design

The mixer circuit is an amalgamation of input signals, a local oscillator, nonlinear devices, and bandpass filters. The nonlinear component is instrumental in achieving frequency conversion, with the local oscillator signal generated in-house. Depending on the chosen nonlinear device, mixers can vary, encompassing diode, transistor, FET, and varactor diode mixers. The crux of mixing involves superimposing two distinct signals onto a nonlinear device, selecting either their sum or difference frequency. For this design, an analog multiplier circuit composed of a transistor-based mixer was selected for its ability to efficiently realize the mixing function, as illustrated in the Figure 1.

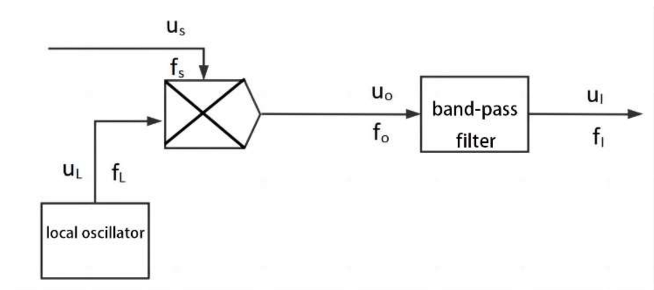

Figure 1. Mixer Circuit Conceptual Diagram

The multiplier harbors two inputs - one for the amplified received signal, denoted as modulated wave uS, and the other for the high-frequency, constant amplitude oscillation uL produced by the local oscillator. The output, uo, encompasses the sum and difference of the input frequencies (fS ±fL). A bandpass filter is then employed to isolate the desired difference frequency.

The design schematic for the analog multiplier mixer circuit is depicted in Figure 2.

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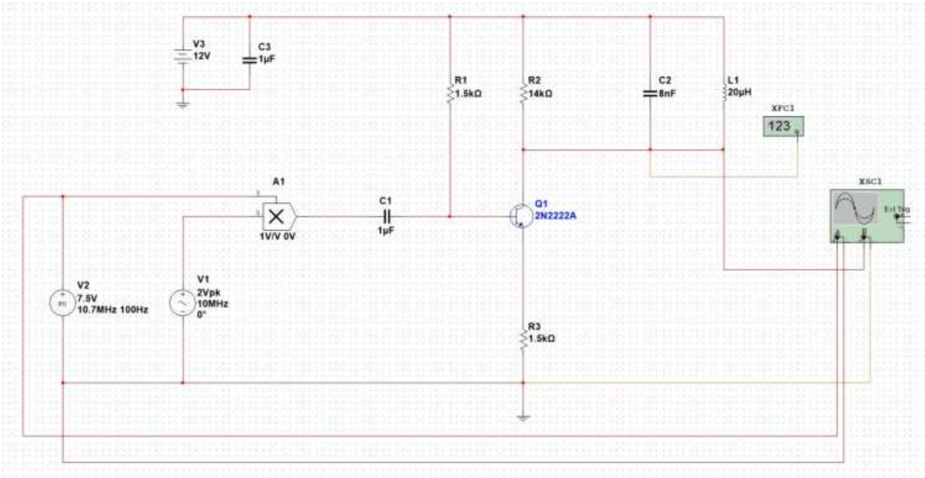

Figure 2. Mixer Circuit Design Schematic

(3) Parameter Calculations and Their Significance in Mixer Circuit Design

A critical phase in the mixer circuit design involves meticulous parameter calculations to ensure the circuit performs optimally at the desired frequencies with high efficiency and selectivity. These calculations include determining the intermediate frequency (IF), the quality factor (Q), and the bandwidth (BW) of the circuit. Each of these parameters plays a pivotal role in the circuit's functionality and overall performance.

1) Intermediate Frequency (IF) Calculation

The Intermediate Frequency (IF) is a fundamental concept in radio receivers, serving as a bridge in frequency conversion processes. For our mixer circuit, the IF represents the target frequency to which the received signal is converted for further processing. It is determined by the resonant frequency (\(f_r\)) of the LC (inductor-capacitor) circuit, calculated using the formula:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Given $(L = 20\ \mu H)$ and $(C = 8\ nF)$, the calculation proceeds as:

$$f_r = \frac{1}{2\pi\sqrt{20 \times 10^{-6} \cdot 8 \times 10^{-9}}} \approx 397.887\ kHz$$

This frequency is crucial because it defines the center of the bandpass filter's passband, ensuring that the circuit selectively amplifies signals at this frequency while attenuating others.

2) Quality Factor (Q) Calculation

The quality factor, or Q, is an indicator of the resonant circuit's selectivity and efficiency. A higher Q value denotes a narrower bandwidth, implying the circuit's heightened ability to select or discriminate against closely spaced frequencies. It is particularly important in communication systems to isolate specific signals from a spectrum of others. The Q of our circuit can be calculated with the formula:

$$Q = \frac{2\pi f_r L}{R}$$

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Given the components' values, $(R = 14\,k\Omega)$, $(L = 20\,\mu H)$, and with (f_r) previously found to be 397.887 kHz, we find:

$$Q = \frac{2\pi \cdot 397{,}887 \cdot 20 \times 10^{-6}}{14 \times 10^{3}} \approx 279$$

This high Q value is indicative of the circuit's effective selectivity, crucial for the FM receiver's ability to accurately filter and process the desired signals.

3) Bandwidth (BW) Calculation

The bandwidth (BW) of the mixer circuit directly influences its ability to process signals within a certain frequency range effectively. It is inversely proportional to the Q factor and can be derived as:

$$BW = \frac{f_r}{Q}$$

Using our determined $(f_r = 397.887kHz)$ and $(Q = 279)$, the bandwidth is calculated as:

$$BW = \frac{397{,}887}{279} \approx 1.426kHz$$

The BW's value signifies the range of frequencies around the IF that the circuit can effectively work with, crucial for ensuring the receiver's versatility and its capacity to demodulate the received FM signal accurately.

(4) Simulation Results

The oscilloscope simulation outcomes of the mixer circuit are showcased in Figure 3, offering a visual testament to the circuit's operational integrity.

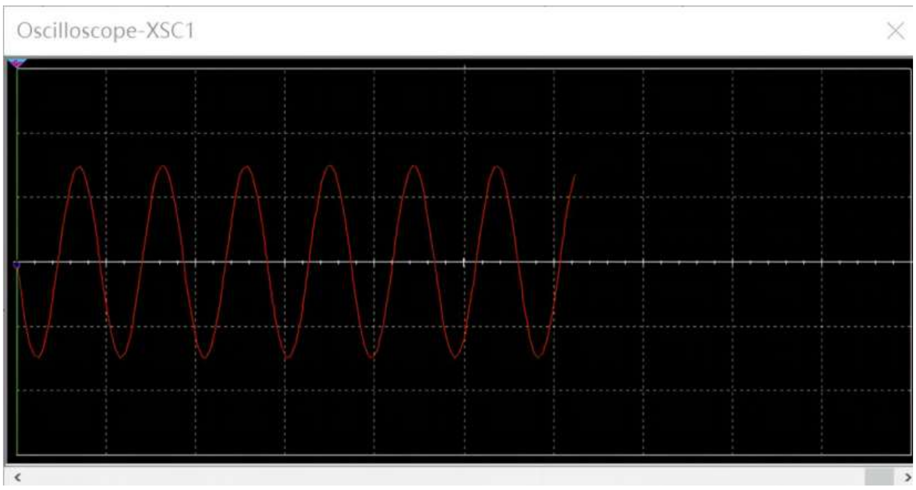

Figure 3. Mixer Circuit Oscilloscope Simulation Results

Frequency counter simulations further affirm the mixer circuit's efficacy, with input signals at 10.7 MHz and 10 MHz, and the resulting difference frequency accurately pegged at approximately 700.993 kHz, virtually nullifying error margins.

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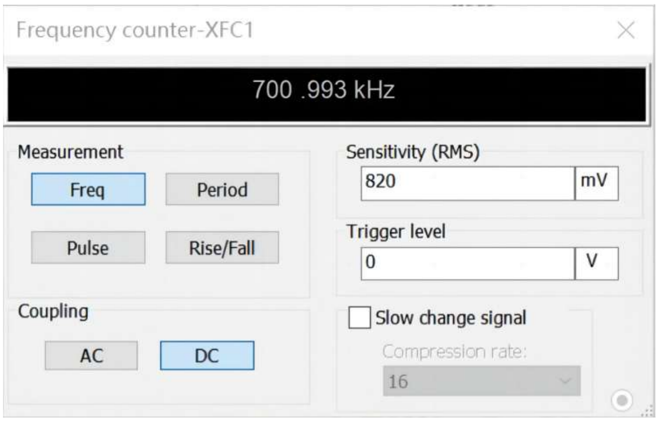

Figure 4. Mixer Circuit Frequency Counter Simulation Results

Frequency counter simulations further affirm the mixer circuit's efficacy, with input signals at 10.7 MHz and 10 MHz, and the resulting difference frequency accurately pegged at approximately 700.993 kHz, as shown in Figure 4, virtually nullifying error margins.

4. Design of the Audio Power Amplifier Circuit

4.1 Design Objectives for the Audio Power Amplifier Circuit

The primary objective was to design an audio power amplifier circuit with a voltage amplification factor (gain) of 20. This specification is crucial to ensure that the signal decoded by the demodulator is adequately amplified for the output stage, achieving the desired loudness and clarity.

4.2 Comparison and Selection of Audio Power Amplification Circuits

In the quest for the optimal low-frequency (audio) power amplifier, several options were evaluated. The goal was to amplify the amplitude of the signal obtained from the demodulator, setting the audio power amplification factor (Auf) at 20.

1) Option 1: LM386 Chip: A low-voltage, general-purpose audio power amplifier widely used in radios, walkie-talkies, and signal generators. It features two signal input ends, with pin 2 as the inverting input and pin 3 as the non-inverting input, each offering an input impedance of 50 KΩ. Its design ensures that even if the input end is short-circuited to the ground, the output DC level remains stable, not deviating significantly.

2) Option 2: LM3886 Chip: A monaural design with 11 pins, offering greater power amplification and a broader dynamic range compared to the LM1857 chip.

3) Option 3: LM1857 Chip: Not only provides power amplification but also includes protection circuits. Designed for monaural output.

After thorough analysis, the LM386 chip was chosen for the low-frequency power amplification circuit due to its stable output DC level even when the input is short-circuited to the ground.

4.3 Analysis and Design of the Audio Power Amplifier Circuit

4.3.1 Circuit Analysis

The LM386 is a versatile chip, with pin 3 serving as the non-inverting input where the signal is introduced. The output from pin 5 passes through a coupling capacitor (220μF). Decoupling filtering is achieved with a 20μF capacitor connected to pin 7. The closed-loop voltage gain of the circuit can be adjusted with a capacitor and resistor connected between pins 1 and 8; changing the resistor value allows the voltage gain to vary between 20 to 200, with lower resistance values yielding higher gains. For high gain requirements, a single 10μF capacitor between pins 1 and 8 suffices. A 10Ω resistor and 0.1μF capacitor connected to the output form an impedance correction network to counteract the reactance in the load, preventing circuit oscillation.

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4.3.2 Circuit Design

The design schematic for the audio power amplifier circuit is shown, catering to the requirements of an FM receiver system.

4.4 Audio Power Amplifier Circuit Test Results

Table 2. Data Results

Signal	Amplitude (U/mV)	Frequency (f/KHz)
Input	170	2.778 (2.735)
Output	3520	2.778

As shown in Table 2, the waveform of the input signal and the amplified output signal demonstrate the circuit's effectiveness in achieving the desired amplification.

4.5 Parameter Calculation

The test results indicate an input signal of 170mV and an output signal amplitude of 3.52V, resulting in a voltage amplification factor of approximately 17.6. This value is remarkably close to the design goal, within an acceptable margin of error, thus validating the success of the design.

Possible sources of error include:

1) Inherent imperfections in the actual circuit board used.

2) Poor connections in the wiring.

3) Variance in the actual values of resistors and capacitors from their nominal values.

4) Internal noise of integrated circuits and the thermal noise of resistors and capacitors.

This chapter elucidates the meticulous approach taken in designing, analyzing, and testing the audio power amplifier circuit, demonstrating a keen focus on achieving high fidelity in signal amplification while addressing practical challenges encountered during the implementation phase.

5. Conclusion

Successful Integration of Components: The design and implementation of the FM receiver system have been successfully achieved by meticulously integrating essential components such as the high-frequency amplifier, mixer, local oscillator, discriminator, and audio power amplifier. This integration ensures the efficient conversion of modulated signals into clear, audible sounds, meeting the primary objective of this project.

Optimization of the Mixer Circuit: Through a comparative analysis of various mixer designs, a hybrid approach combining the transistor-based and analog multiplier mixer circuits was adopted. This choice was substantiated by the precise calculations of intermediate frequency (IF), quality factor (Q), and bandwidth (BW), which underscore the mixer circuit's capability to enhance the receiver's sensitivity, selectivity, and overall stability.

Effective Audio Power Amplification: The selection of the LM386 chip for the audio power amplifier circuit was validated by rigorous testing and parameter calculations. Achieving a voltage amplification factor close to the target of 20, the designed circuit exhibits exceptional performance in amplifying the decoded signal to the desired loudness and clarity without significant deviation or distortion.

Experimental Validation: Test results from both the mixer and audio power amplifier circuits have demonstrated the theoretical designs' effectiveness in practice. While minor discrepancies were observed, these were within acceptable error margins, attributing to the intrinsic challenges of practical circuit design and implementation, such as component variance and thermal noise.

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Future Directions: This study lays a solid foundation for further research and development in FM receiver systems. Future work could explore the integration of advanced signal processing techniques, the utilization of more sophisticated components for improved efficiency, and the expansion of the receiver's capabilities to accommodate digital broadcasting standards.

In conclusion, this paper presents a comprehensive design strategy and implementation framework for an FM receiver system, achieving notable advancements in signal processing, frequency mixing, and audio amplification. The successful realization of this project not only contributes to the academic and practical understanding of FM receiver systems but also opens avenues for further innovation in the field of communication systems.

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