Basic Principles and Typical Circuit Analysis of Operational Amplifiers

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Abstract. This article explores the fundamentals of operational amplifiers, focusing on their ideal characteristics and basic circuit configurations. Op-amps are integral components in analog electronics, used in a wide range of applications such as amplification, filtering, and signal processing. The ideal op-amp is characterized by infinite open-loop gain, infinite input impedance, and zero output impedance, simplifying circuit analysis. Key concepts like "virtual short circuit" and "virtual open circuit" are discussed, which are crucial for understanding how op-amps operate in feedback configurations. The study delves into inverting and non-inverting amplifier circuits, providing a theoretical analysis that was validated through simulation in Multisim software. These simulations confirmed that assuming an ideal op-amp yields simplified and accurate analysis in most cases. However, the study also highlights practical limitations such as limited gain bandwidth, which affects real-world applications. The research offers valuable insights into op-amp behavior, serving as a foundation for designing more complex and practical electronic circuits.

Keywords: Operational Amplifiers, Circuit Analysis, Circuit Simulation.

1. Introduction

An operational amplifier is one of the most commonly used components in analog electronic circuit design. This high-gain voltage amplifier with differential input has become a fundamental component of modern electronics. Operational amplifiers have been applied in signal conditioning, active filtering, analog computing, and sensor interfaces [1]. Its operational theory is based on several idealized assumptions, which greatly simplify circuit analysis while providing valuable insights into its behavior. In this study, I first explored the concepts of "virtual short circuit" and "virtual open circuit", which are key to simplifying the analysis of operational amplifiers. Then I verified their applicability through the practice of non-inverting amplifier circuits.

The development of operational amplifiers can be traced back to the 1940s, when they were used in analog computers to perform mathematical operations, and hence their name. The integrated circuit operational amplifier developed in the 1960s was invented, which provides excellent characteristics very close to the ideal amplifier model. Modern devices typically have high input impedance, low output impedance, and very high open-loop gain [2]. These characteristics make it indispensable in both simple circuits and complex industrial systems.

It is important to understand the practical significance of the basic principles of operational amplifiers. In the educational environment, mastering basic operational amplifier circuits provides students with key analytical tools for more advanced electronic concepts. For engineers, these principles form the foundation for designing complex simulation systems. The concept of "virtual short circuit" originates from the extremely high gain of amplifiers, which simplifies node analysis by assuming that the voltage difference between input terminals is close to zero. Similarly, the concept of "virtual openness" caused by high input impedance allows for the assumption that the input current can be ignored [3]. These approximations together provide elegant solutions for complex circuit analysis problems.

This investigation focuses on two fundamental op-amp configurations: the inverting and non-inverting amplifiers. Through detailed theoretical analysis supported by computer simulations using Multisim, we demonstrate how these basic circuits operate and how their performance can be predicted using ideal op-amp principles. The study also examines the limitations of the ideal model by comparing theoretical predictions with simulated results, particularly addressing discrepancies caused by finite gain bandwidth product and input offset voltages.

This study mainly focuses on two basic configurations of operational amplifiers: inverting amplifiers and non-inverting amplifiers. By using Multisim's computer simulation support and detailed theoretical analysis, I demonstrated how these basic circuits work and how to predict their performance using ideal operational amplifier principles. The study also examined the limitations of the ideal model, particularly the differences caused by the finite gain bandwidth product and input offset voltage, by comparing theoretical predictions with simulation results.

Contemporary literature on operational amplifiers, including groundbreaking works such as Horowitz and Hill's "The Art of Electronics as well as manufacturer application notes from Texas Instruments and ADI, comprehensively covers both theoretical and practical aspects [4, 5]. However, effective methods are still needed to bridge the gap between abstract theory and practical implementation. This article aims to delve into the principles of operational amplifiers and verify them through experiments.

This method combines rigorous mathematical deduction with computer simulation to enhance conceptual understanding. Starting from the assumption of an ideal operational amplifier, I derived the closed-loop gain equations for two amplifier configurations. Then, by verifying these theoretical results through circuit simulation, the actual behavior of the components can be observed. This dual approach not only confirms the effectiveness of the theoretical model but also demonstrates the practical considerations required for successfully implementing the circuit.

2. Method, Results, and Discussion

2.1. Research Methodology

Theoretical Framework. This study establishes an analytical framework based on an ideal operational amplifier model, which includes three assumptions: first, the open-loop gain is close to infinity; second, the input impedance is infinite; third, the output impedance is zero. Based on these ideal assumptions, two key concepts have been derived: the first is the concept of virtual short circuit, where the voltage at the non-inverting and inverting terminals is equal; And the concept of virtual open circuit: input current is zero [6].

Circuit Configurations. Two basic op-amp circuit configurations were selected for comparative study: the first is the inverting amplifier configuration, where the input signal is connected to the inverting input through resistor R1, with feedback resistor Rf forming a negative feedback network; the second is the non-inverting amplifier configuration, where the input signal is directly connected to the non-inverting input, with feedback implemented through a voltage divider network consisting of R1 and Rf.

Analytical Approach. For each circuit configuration, a systematic analysis method is adopted: first, Kirchhoff's current law is applied at key circuit nodes; Then, use the ideal conditions of virtual short circuit and virtual open circuit; Finally, derive the theoretical expression for the closed-loop gain. The voltage gain formula for an inverting amplifier is A=- Rf/R1, while the formula for a non-inverting amplifier is A=1+Rf/R1 [7]. These theoretical derivations provide a reference benchmark for subsequent simulation verification.

Simulation Methodology. Simulation experiments were conducted using Multisim 14.2 software, employing the LM324 operational amplifier model. Experimental settings included: configuring a symmetrical 5V AC power supply; setting resistor values at R1=1kΩ and Rf=2kΩ; establishing voltage waveform measurement points at the input and output; and performing frequency sweep analysis from 10Hz to 1MHz to comprehensively evaluate circuit performance.

2.2. Experimental Results

Ideal Circuit Analysis. Theoretical calculations have yielded the expected result: the theoretical gain of the inverting amplifier at 180-degree phase reversal is -2, while the theoretical gain of the non-inverting amplifier at output and input in phase is +3. These theoretical values serve as benchmarks for evaluating the performance of actual circuits.

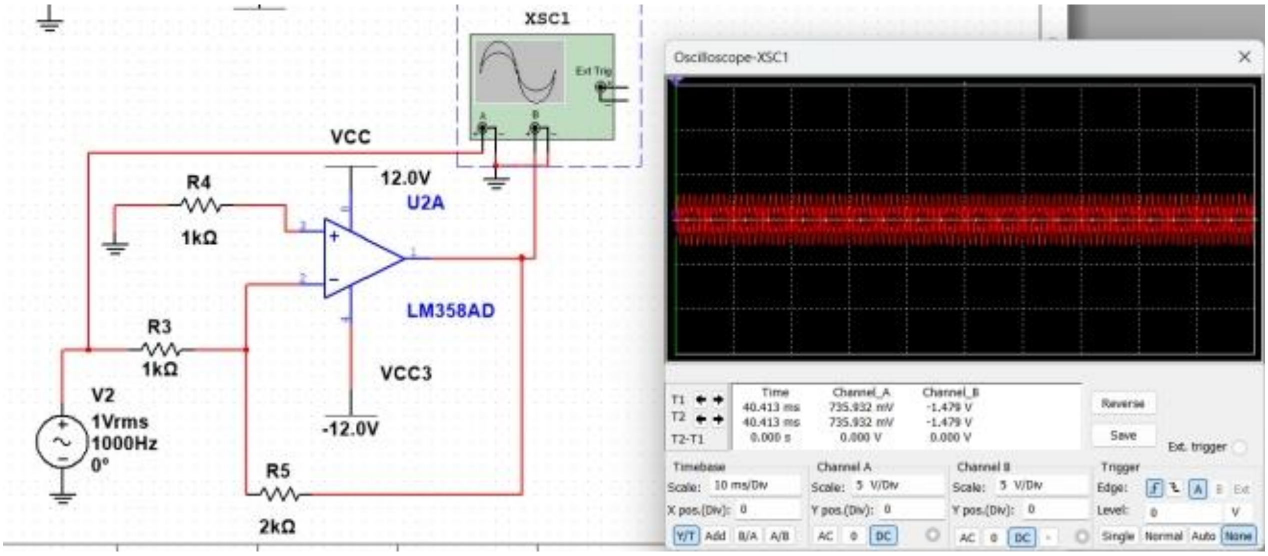
Simulation Data.

Time Domain Analysis. The amplification factor of a Inverting amplifier is equal to the negative value of the feedback resistance compared to the input resistance. In simulation, at 1kHz operating frequency, when the feedback resistor resistance is 2 ohms and the input resistor resistance is 1 ohm measured data showed: the inverting amplifier circuit achieved an actual gain of -2.010, representing a 0.50% deviation from theory (Refer to Figure 1), along with the expected 180-degree phase inversion.

$$Av = Vout / Vin = - (Rf / R1) \tag{1}$$

When the resistance values are the same, the amplification factor of the in-phase amplifier is equal to the feedback resistance plus the input resistance plus 1. The non-inverting amplifier circuit showed an actual gain of +2.978, with a 0.73% deviation (Refer to Figure 2), while maintaining a 0-degree phase relationship.

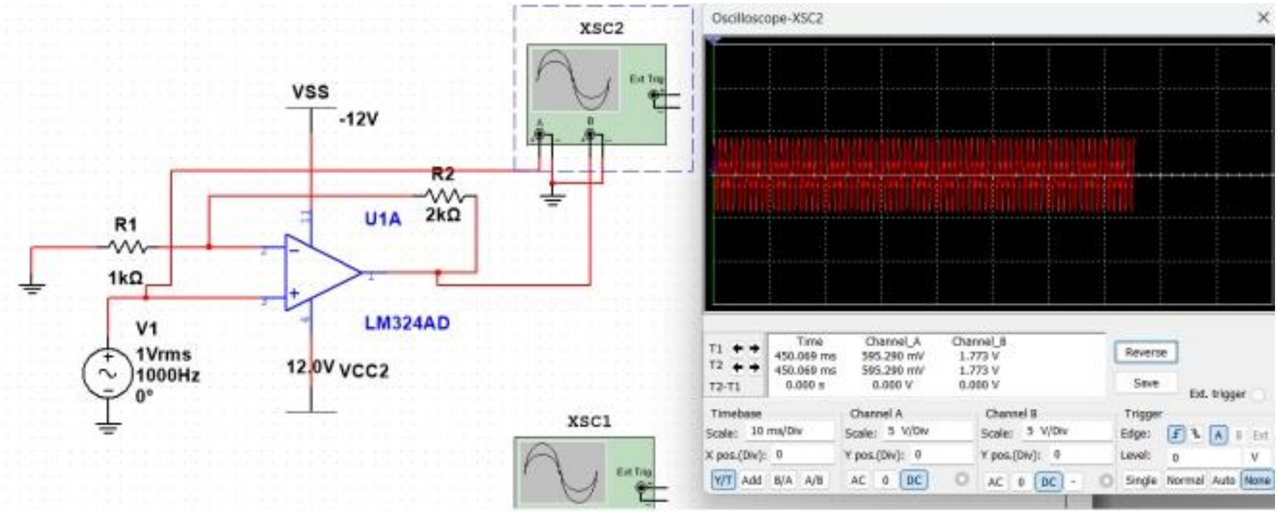
$$Av = Vout / Vin = 1 + (Rf / R1) \tag{2}$$



	Time	Channel_A	Channel_B
T1	40.413 ms	735.932 mV	-1.479 V
T2	40.413 ms	735.932 mV	-1.479 V
T2-T1	0.000 s	0.000 V	0.000 V

Timebase Scale: 10 ms/Div
X pos.(Div): 0
Channel A Scale: 5 V/Div
Y pos.(Div): 0
Channel B Scale: 5 V/Div
Y pos.(Div): 0
Trigger Level: 0 V

Fig. 1 Inverting amplifier simulation



	Time	Channel_A	Channel_B
T1	450.069 ms	595.290 mV	1.773 V
T2	450.069 ms	595.290 mV	1.773 V
T2-T1	0.000 s	0.000 V	0.000 V

Timebase Scale: 10 ms/Div
X pos.(Div): 0
Channel A Scale: 5 V/Div
Y pos.(Div): 0
Channel B Scale: 5 V/Div
Y pos.(Div): 0
Trigger Level: 0 V

Fig. 2 Non-inverting amplifier.

Frequency Response. Frequency characteristic testing shows that both circuit configurations exhibit significant bandwidth limitations. The 3dB cut-off frequency of the inverting amplifier appears at 82kHz, while the cut-off frequency of the non-inverting amplifier is slightly lower at 75kHz. The calculated gain bandwidth product of the two circuits is approximately 800kHz, which complies with the LM324 specification [8].

Non-Ideal Effects. Several non-ideal characteristics were observed during high-frequency testing: firstly, due to the limited gain bandwidth product, the gain decreases with increasing frequency. Secondly, the phase margin gradually decreases. Thirdly, an output AC offset voltage of approximately 2mV was detected, mainly due to the effect of input offset voltage.

2.3. Analysis and Discussion

Ideal Model Verification. In the low-frequency range (<1kHz), measured results closely matched theoretical predictions: the inverting amplifier showed only 0.5% gain error, and the non-inverting amplifier 0.73%. These results strongly validate the practical value of the ideal op-amp model for basic circuit analysis, demonstrating that ideal assumptions can provide sufficient accuracy for engineering estimations under appropriate conditions

Limitations and Deviations. In-depth study of observed deviations revealed important op-amp non-ideal characteristics: first, the finite gain-bandwidth product directly caused high-frequency response attenuation, with results completely consistent with LM324 technical specifications, vividly demonstrating the ubiquitous speed-accuracy trade-off in analog circuits; second, while the DC offset caused by input offset voltage was minimal, it could have significant impact in high-gain applications; furthermore, waveform distortion observed at high frequencies (>100kHz) clearly showed the effect of slew rate limitations on signal fidelity.

Design Implications. Based on experimental results, several important design guidelines were summarized: for AC or low-frequency applications, the ideal model provides sufficient analytical accuracy, and most non-ideal effects can be neglected; when wider operating bandwidth is required, op-amp models with higher gain-bandwidth product should be selected, with gain-bandwidth compensation techniques employed when necessary; for high-precision applications, the influence of input offset voltage must be fully considered, typically requiring nulling circuits for compensation [9,10].

3. Conclusion

This study comprehensively examined the fundamental principles and practical applications of operational amplifiers, with a focus on their ideal behavior and real-world limitations. By combining theoretical analysis with Multisim simulations, the research validated the effectiveness of the "virtual short" and "virtual open" concepts in simplifying circuit analysis, particularly in low-frequency applications. The inverting and non-inverting amplifier circuits demonstrated close alignment with theoretical predictions, exhibiting minimal deviations (less than 1%) in gain and phase characteristics. However, the study also identified critical non-ideal effects, including finite gain-bandwidth product and input offset voltage, which become significant at higher frequencies and in precision applications. These findings underscore the importance of selecting appropriate operational amplifier models and employing compensation techniques in practical designs. The results provide valuable insights for both educational purposes and engineering applications, reinforcing the need to balance ideal assumptions with real-world constraints. Future research could further explore advanced compensation methods and the integration of operational amplifiers in more complex systems to enhance performance and reliability.

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