Verification and Optimization of an Operational Amplifier Utilizing a Designed Experiment

Alan Windham, James Z. Zhang, Aaron K. Ball
Kimmel School of Construction Management, Engineering, and Technology
Western Carolina University, Cullowhee, North Carolina, 28723
Awindham@ieee.org, zhang@email.wcu.edu, ballaaron@email.wcu.edu

Abstract

Operational Amplifiers (Op-Amp) have been an intricate part of life for more than half a century. Op-Amps are used in virtually all electronic devices. Because an Op-Amp's operational characteristics are affected by many variables such as bias and input signal frequency, it is imperative to verify and optimize its parameters under various operating conditions. In doing so, it is expected to improve simulation accuracy and hence implementation quality.

The main objectives of this research were to broaden basic knowledge of Op-Amp circuits, and in particular, gain in-depth understanding of the impact of frequency and bias on operating characteristics of Op-Amp circuits. Focus was on properly simulating practical Op-Amp reactions to fluctuations of several parameters such as bias voltage, frequency, and current. An experiment using these parameters was designed to determine modeling accuracy of the Op-Amps. A two-level factorial design was implemented to discover the actual significant parameters and their interactions. Testing data was compared with those obtained from a Simulation Program with Integrated Circuit Emphasis (SPICE) program, and statistical inference was drawn from data analysis and suggestions are given to optimize simulation parameters.

The expected results from this project were to gain extensive knowledge of Op-Amp circuit design and implementation. Simulation tools such as Cadence's PSpice® circuit simulation software were used to aid the design.

Introduction

The purpose of this research project has been the verification and optimization of how an operational amplifier operates. Focus has been on properly simulating how a LM741 operational amplifier (op-amp) reacts to the fluctuations of a few parameters. Parameters such as bias voltage and frequency were varied between three and four levels in a designed experiment. Preliminary analysis was completed using a designed experiment to determine significant individual parameters and any significant interactions that exist.

To properly simulate the op-amp an equivalent model was developed and a SPICE program developed to predict the op-amp functions. Preliminary statistical analysis that included a two factorial design analysis was performed. One of the goals was development of equations that aid in the prediction of op-amp behavior without running computer simulations for every possible combination of parameter fluctuations. Efforts focused on fine tuning the model by analysis of real world op-amp performance, specifically looking at the transient response output from an inverting op-amp. The expected results from this project were to gain extensive knowledge of op-amp circuit design and implementation. Simulation tools such as Cadence's PSpice® circuit simulation software were used to aid the design.

Literature Review

The operational amplifier was originally designed to perform mathematical operations - hence its name - by using voltage as an analogue of another quantity. This is the basis of the analogue computer where op-amps were used to model the basic mathematical operations (addition, subtraction, integration, differentiation, and so on). An ideal operational amplifier is an extremely versatile circuit element, with a great many applications beyond mathematical operations. Practical op-amps based on transistors, tubes, or other amplifying components and implemented as discrete or integrated circuits, are approximations to the ideal [1].

Operational amplifiers were originally developed in the vacuum tube era (1950’s), where they were used in analog computers [2]. Operational amplifiers are now normally implemented as integrated circuits (ICs), though versions with discrete components are used when performance beyond that attainable with ICs is required [3].

The first integrated op-amp to become widely available, in the late 1960s, was the bipolar Fairchild µA709, created by Bob Widlar in 1965; it was rapidly superseded by the µA741, which has better performance and is more stable and easier to use [4]. The µA741 is still in production, and has become ubiquitous in electronics—many manufacturers produce a version of this classic chip, recognizable by containing "741" in the part number. Better designs have since been introduced, some based on the field-effect transistor (FET) and metal-oxide semiconductor field-effect transistor (MOSFET). Many of these more modern devices can be substituted into an older 741-based circuit and work with no other changes, to give better performance [4].

Operational amplifiers usually have parameters within tightly specified limits, with standardized packaging and power supply needs. Operational amplifiers have many uses in electronics—the op-amp is probably the most useful single device in analog electronic circuitry [4]. With only a handful of external components, it can be made to perform a wide variety of analog signal processing tasks.

Experiment Setup

The designed experiment was based around a basic inverting operational amplifier circuit which is represented in Figure 1. The fundamental principle of an inverting op-amp is that whatever signal goes in comes out at 180 degrees inverted, multiplied by the gain. Figure 1 was drawn and tested within PSpice®. PSpice® is an electronics industry staple for engineers designing or improving circuits. The main advantage of PSpice® is it allows a designing engineer to investigate the behavior of a circuit without having to actually construct a physical circuit [5].

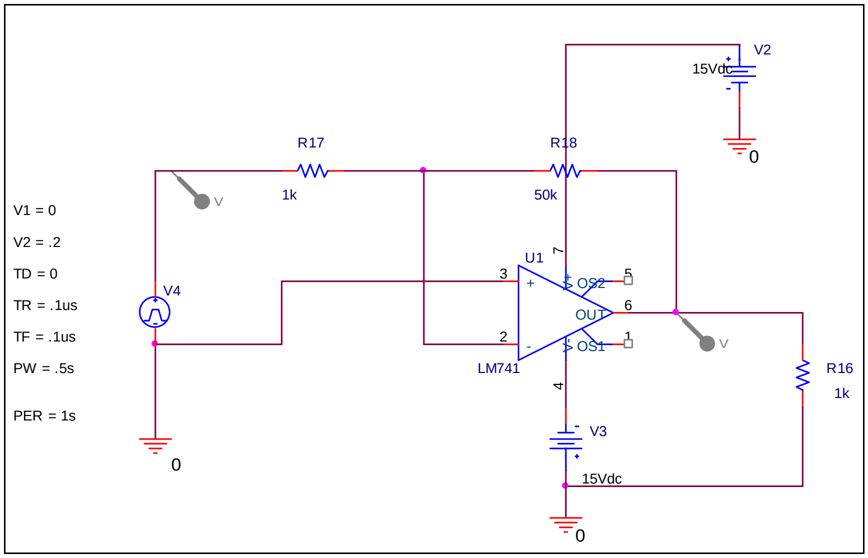

Fig. 1 Test Circuit

The input to the circuit was a square wave frequency with a 50% duty cycle varying from 20 Hz to 100 kHz. The voltage bias of the circuit was controlled by resistors R18 and R17. The voltage bias, or other wise known as *gain*, is denoted as A_{cl} was determined by the ratio of R18/R17 (i.e. $A_{cl} = R18/R_{17}$). The gain was varied from 1 to 50. The frequency and gain varied values were determined through a process of elimination and reference to the percentage of ideal operating parameters of a LM741 op-amp, which was referenced from the manufacturer of the LM741, National Semiconductor spec sheets [6].

There are several parameters that were blocked within this designed experiment, meaning they were assumed to be constant or insignificant for the scope of this research. The parameters that were assumed to be blocked were: temperature of op-amp and other components; variations of voltage output from the 10V; noise that may have entered the circuit during testing; and input variations from the desired. The signal generator that was used for the experiment was an Aligent 54622D Mixed Signal Generator, the power supply that was used was an Aligent E3631A Triple Output DC Power Supply, and the signal generator that was us was an Aligent 33250A 80MHz Function/Arbitrary Waveform Generator.

The op-amp PSPICE® model was simulated and the transient response data was collected through the PSPICE®. The actual op-amp circuit was setup and 48 runs were performed to gather all the required transient response (or other wise known as rise time) data points through the use of the Aligent oscilloscope. The results of the collected data are shown in Table 1.

Table 1. Simulation and Circuit Response Variables

Freq (Hz) / Bias (Gain)	Circuit 20	Simulated 20	Circuit 25k	Simulated 25k	Circuit 50k	Simulated 50k	Circuit 100k	Simulated 100k
High 50	1.90E-06	2.37E-05	1.90E-06	2.45E-05	1.90E-06	2.45E-05	1.88E-06	2.33E-05
High 50	1.88E-06	2.37E-05	1.85E-06	2.45E-05	1.88E-06	2.45E-05	1.90E-06	2.33E-05
High 50	1.95E-06	2.37E-05	1.90E-06	2.45E-05	1.95E-06	2.45E-05	1.85E-06	2.33E-05
Medium 25	2.50E-06	1.93E-05	1.55E-06	2.04E-05	2.20E-06	2.04E-05	2.65E-06	2.03E-05
Medium 25	2.55E-06	1.93E-05	1.55E-06	2.04E-05	2.10E-06	2.04E-05	2.60E-06	2.03E-05
Medium 25	2.60E-06	1.93E-05	1.65E-06	2.04E-05	2.25E-06	2.04E-05	2.65E-06	2.03E-05
Low 1	1.70E-07	1.80E-05	1.75E-06	1.79E-05	1.80E-06	1.79E-05	1.80E-06	1.80E-05
Low 1	1.65E-07	1.80E-05	1.75E-06	1.79E-05	1.81E-06	1.79E-05	1.82E-06	1.80E-05
Low 1	1.70E-07	1.80E-05	1.75E-06	1.79E-05	1.85E-06	1.79E-05	1.80E-06	1.80E-05

Figure 2 represents plotted averaged transient responses from both the simulated and actual circuits. Notice that simulated op-amp's transient response was longer than the actual circuit's response.

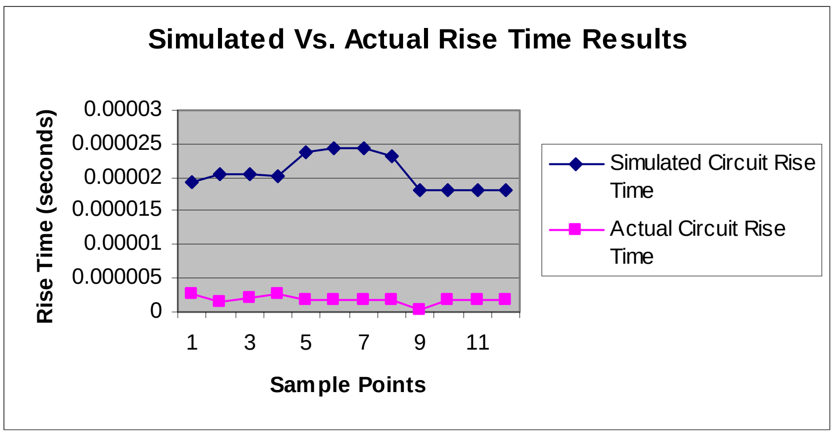

Fig. 2 Simulated Versus Actual Rise Time Results

It was determined to use a 3^2 factorial design based on the given data to perform the evaluation of the transient response data. The transient response data was manipulated with the Excel Add-in Data Analysis package, ANOVA: two-factorial design with replication. The summary ANOVA table results from the software package are shown in Table 2.

Notice in Table 2 that the F-statistic for Gain, Frequency, and Interaction are all greatly higher than F-critical. This tells us that all the factors and interactions are statistically significant for this research. To produce a viable solution from the data, the actual data taken for each interaction or setting of frequency versus gain was averaged and subtracted from the simulated data. This subtraction created time differences between the simulated data and actual circuit data. The results from performing the averaging and differences are shown within Table 3. The

Table 2 Summary ANOVA Table

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Gain	4.4E-12	2	2.2E-12	1518.098	5.41E-26	3.402826

Frequency	1.67E-12	3	5.58E-13	384.7829	2.03E-20	3.008787
Interaction	6.33E-12	6	1.05E-12	727.1665	6.47E-26	2.508189
Within	3.48E-14	24	1.45E-15			
Total	1.24E-11	35				

differences can be applied to the SPICE simulated output for more accuracy during design and implementation.

Table 3 Time Differences between Simulated and Actual Circuit and Percent Rise Time/1 Period

Freq (Hz) / Bias (Gain)	20	25k	50k	100k
High 50	-2.18E-05	-2.26E-05	-2.26E-05	-2.14E-05
% Rise Time/1 Period	0.0038%	4.71%	9.55%	18.75%
Medium 25	-1.67E-05	-1.88E-05	-1.82E-05	-1.76E-05
% Rise Time/1 Period	0.0051%	3.96%	9.10%	26.33%
Low 1	-1.78E-05	-1.62E-05	-1.62E-05	-1.62E-05
% Rise Time/1 Period	0.0003%	4.38%	6.51%	18.07%

Also notice within Table 3 that there are 3 rows labeled "% Rise Time/1 Period". The % rise time per 1 period represent the percentage of the rise time for the given frequency (i.e. 20Hz, 25 kHz, etc.). In other words, the percentage represented is the actual circuit transient response divided by the time of period for the associated frequency (e.g. 20 Hz = 0.05 seconds per period). There is a direct correlation to the percentage of transient response to the amount of frequency applied to the op-amp. As the frequency increases, so does the amount of transient response per period. This was expected, and therefore is verified with this calculation. The idea behind the lag as frequency is increased is that the op-amp is not able to keep up with the higher frequencies as easily as the lower frequencies.

Further comparisons of physical op-amps to the simulation model could increase the accuracy of predicting the resulting transient response (rise time), making op-amp circuit design and manufacturing a more efficient business enterprise. Expanded research into the transient response and input signals devices could make the simulation model better reflect how op-amps are operated in the many devices that currently use them.

Bibliography

[1] Lythall, Harry., Operational Amplifier Basics. Retrieved on May 6, 2006, from: http://web.telia.com/~u85920178/begin/opamp00.htm, 2006.

[2] Mastascusa, E. J., The Inverting Amplifier. *Bucknell University*. Retrieved on May 6, 2006, from: http://www.facstaff.bucknell.edu/mastascu/eLessonsHTML/OpAmps/OpAmp2.html. 2006

[3] Floyd, Thomas L., *Electronic Devices,* 5th Edition. Prentice-Hall., 1999. pp. 632-807.

[4] Wikipedia. *Operational Amplifiers.* Retrieved on April 20, 2006, from: http://en.wikipedia.org/wiki/Operational_amplifier. 2006

[5] Baldwin, Michael. *Development and Verification of a Relay Coil Simulation Model Utilizing A Designed Experiment.* Western Carolina University. IET 680 Independent Research Project. 1997.

[6] National Semiconductor. *LM741 Operational Amplifier.* Retrieved on April 21, 2006, from: http://www.national.com. 2000.

Biography

ALAN P. WINDHAM received the B.S. in Electrical and Computer Engineering Technology (2005) from Western Carolina University. Recently he received his M.S. in Technology from the School of Technology at Western Carolina University. He is a member of the IEEE and SAE.

JAMES Z. ZHANG received the B.S.E.E. (1986) from Hunan University, PRC. He received the M.A. (1993) in Telecommunications from Indiana University, M.S.E. (1993) and Ph.D. (2002) in Electrical and Computer Engineering from Purdue University. Currently he is an Assistant Professor of Electrical Engineering in the School of Technology at Western Carolina University. He is a member of ASEE and senior member of IEEE.

AARON K. BALL is an Associate Professor and serves as the Graduate Program Director in Engineering and Technology at Western Carolina University in Cullowhee, North Carolina. He holds a B.S. and an M.S. from Appalachian State University, and earned his doctorate from Virginia Polytechnic Institute and State University. His areas of interests include fluid power, advanced machining, prototyping systems, and applied research.