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大学电子信息科学与技术英汉实验丛书

模拟电路实验

陈孝桢 张丽敏 编著

南京大学出版社

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前　言

模拟电路实验是电子科学与工程类专业本科的一门重要的基础实验课。近几年来，我一直在思考，面对电子科学和技术日新月异的进步，在整个教学计划中，模拟电路实验的教学目的是什么？通过这门实验课教学，希望使学生学到些什么？应该做哪些实验？如何做这些实验？

我以为，电子科学与工程学科本科的教学目的，是使学生毕业后能从事现代电子设备的使用、维护和设计研究工作，为学生在电子科学与工程方面的进一步深造或自学打下坚实的基础。也就是说，他们最终都要面对实际的电子系统。学生在做模拟电路实验之前，在课堂教学中学到的模拟电路知识通常是基于理想元件的基本单元电路的理论知识。通过模拟电路实验，要使学生认识实际元件，分析实际电路，学习使用当代的常用电子测量仪器，学习使用电路分析与设计软件，了解现代电子系统的组成和特点。因此，模拟电路实验是模拟电路课堂理论教学的继续和深入，学生需要学习许多新知识。

根据上述认识，选取教学内容。作为电子技术基础实验，模拟电路实验仍然以对传统典型电路做验证性实验为主，因为它们是电子科学与技术基础的重要组成部分。然而，它们与实验结果相验证不是基于理想元件的电路分析得到的结果，而是计及实际元件参数的电路分析结果。在此基础上适当增加了一些新的内容，使得本实验教材对教学内容、教学要求做了较大的更新，特别突出以下三方面的要求：

1. 强调计及实际元件参数，对电路作精密分析；强调用信号与系统的理论分析线性电路；强调用计算机软件做电路仿真，在此基础上对电路做验证实验。

2. 强调用好数字式仪器。不仅要求学生会动手操作，还要求其知道最基本的仪器构成及其基本工作原理。因为只有了解仪器的构成与基本原理，才能真正用好仪器。要求学生知道数字式仪器与计算机构成测量系统的工作原理与使用操作方法，使其了解现代电子系统的设计思想和基本组成。

3. 强调阅读英文资料。因为大量电子科学与技术的原创性资料是用英文书写的，所以只有通过阅读英文资料，才能获得具体的知识，才能更快、更准确地获取其所载有的信息。

本书共安排 13 个实验。其中，前 11 个实验是验证性实验，实验 12 是设计性实验，实验 13 是综合性实验。实验 13 可编程放大器实验作为开放实验，在课程时间以外供学生选做。

本实验教材是在 2005 年南京大学出版社出版的《模拟电路实验》的基础上，根据如今

学院的教学要求改写而成。其中，实验13由南京大学电子科学与工程学院张丽敏编写，其余由南京大学金陵学院信息科学与工程学院陈孝桢编写。

本实验教材是在不断思考、研究、教学相长的过程中形成的。我认为，这样的过程仍然在继续中。真诚地希望所有使用本教材的教师和学生，对本教材提出改进的意见，对本教材中不正确的地方给予指正。

陈孝桢
2013年3月

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Introduction

绪 论

1. About analog circuit experiments

One of the ultimate goals for the study and research of electronic science and technology is to design and manufacture a variety of electronic equipment.

A modern circuit typically contains analog circuits, digital circuits and computer circuits. Circuit systems consisting of analog circuits are becoming less and less. Analog circuitry is, however, often part of the circuit system. Thus analog circuit theory and technology is one of the major topics in microelectronic circuit design.

The procedure of learning circuit design could be divided into three phases: basic circuit theory, unit circuit design and fabrication, circuit system design and manufacturing. For analog circuits, the course about analog circuits taught in the classroom covers basic circuit theory, which could be considered as the first phase of learning about analog circuits. This course is aimed at verifying basic circuit theory, laying the foundation for unit circuit design and fabrication, which could be considered as the second phase. In addition, there is an experiment which could be considered as an initial, relatively simple circuit system design practice.

Analog circuit experiments is a course of further learning analog circuits by experiments after the analog circuit theory course, which is a critical phase of learning about analog circuits.

2. Contents of learning in this course

(1) Use learned knowledge to do verifying experiments

In the experiments, students will learn to use oscilloscopes, signal generators, multimeters, dc power supply sources, etc. They will learn to recognize the physical significance, physical dimension, accuracy, etc. of data obtained by instruments. They will also learn to use common circuit drawing, simulation, analysis, printed circuit board design software applications, such as EWB and Protel; and learn to use common circuit experiment tools, such as a breadboard and soldering iron.

(2) Read component datasheets

Components shown in the analog circuit textbooks are mostly ideal components. You will choose suitable nominal components in circuit design. You will inevitably encounter real components in analog circuit experiments. Moving from a theoretical knowledge of the ideal component to an understanding of the nominal component, and finally to a concrete ability to use the real component requires a substantial amount of learning.

Take a resistor as an example. In the ideal component, there is only one parameter to describe a resistor; namely, the resistance value. In the nominal component, there are at least the following characteristics: material, structure, rating power, nominal value and accuracy. In the real component, beyond the descriptions of nominal component there are at least the following characteristics: thermal stability, aging characteristic, component quality grade, etc. Also, the real resistance value of the resistor is usually similar to the nominal value of the resistor, but not exactly equal to the nominal value.

Take an op-amp as another example. For an ideal op-amp, there are at least the following assumptions: open-loop gain is infinite, input impedance is infinite, common mode rejection ratio is infinite, input offset voltage is zero, input offset current is zero, and the output resistance is zero. There are a great variety of op-amps. The op-amps used in this experimental course are the LF351 and the OP07, the datasheets of which can be found at http://www.21ic.com/. The datasheet of an op-amp describes the nominal op-amp which is more complex than the ideal op-amp. The nominal op-amp is the basis for op-amp circuit design and analysis. A performance parameter in the datasheet of a nominal op-amp is often given minimum, typical, and maximum values; this shows that the performance parameters of real op-amps with same type may be different from each other, but should be within the performance parameter range of the nominal op-amp.

Due to the differences between real components and ideal components for a circuit, the performance of the real circuit and the performance of the circuit designed with ideal components are different; sometimes these differences may be large. Therefore, analyzing a real circuit must take the relevant parameters of the real components into account, which complicates the analysis. Taking real component performance parameters into account, using the theory of linear systems to analyze the experimental circuit, allow results obtained by the analysis to often correspond quite closely with the real measured results. This is very useful for precision circuit design.

(3) Analyze unfamiliar circuits by applying knowledge learned

For example, in Lab 4, students analyze the equivalent internal circuit of the integrated power amplifier LM386; in Lab 10, they analyze magnitude frequency characteristic of the fourth-order low-pass filter.

(4) Design circuits by applying knowledge learned

For example, Lab 12 requires the experimenter to design a small-signal amplifier.

(5) Design part of an electronic system by applying knowledge of analog circuits from this course, along with knowledge from other courses

For example, Lab 13 requires the design of a programmable amplifier, along with the input dynamic compression and A/D sampling circuit.

3. Examples of issues in circuit design and analysis

(1) The interference in a circuit caused by dc power source coupling

Consider the example shown in Figure 0 - 1, in which there are a small-signal circuit and a large-signal circuit in the same circuitry. The current from the dc power source to the large-signal circuit through the equivalent power source internal resistor R_s causes the output voltage dc power source fluctuation. For the small-signal circuit, the transistors would directly or through resistors and other components be linked with the dc power source, so that the output voltage fluctuation of the power source caused by the large-signal circuit would inevitably appear in the output of the small-signal circuit. In some circuitry without dc power supply decoupling circuit, the voltage fluctuation coupled to the small-signal circuit could even prevent the whole circuit from working normally.

Consider also the example shown in Figure 0 - 2, in which a decoupling circuit is added. When the current to the large-signal circuit is small, the dc power source supplies current to the large-signal circuit and at the same time, charges the capacitor E_1, the dc current from the dc power source is not reduced much. When the current required by the large-signal circuit is large, at the moment when the output voltage of the dc source begins to decrease, both the dc power source and the capacitors supply current to the large-signal circuit instantaneously, so the dc current from the dc power source is not increased much. Thus the output voltage fluctuation of the dc power source is greatly reduced. For the small-signal circuit, through the decoupling circuit filtering, the voltage fluctuations of the dc power supply to the small-signal circuit are further reduced. By choosing appropriate values of R and C in the decoupling circuit, the interference caused by the power source coupling can be reduced to a tolerable level.

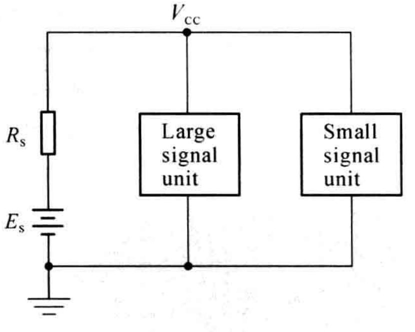

Figure 0 - 1 Illustration of dc power source coupling and grounding path coupling

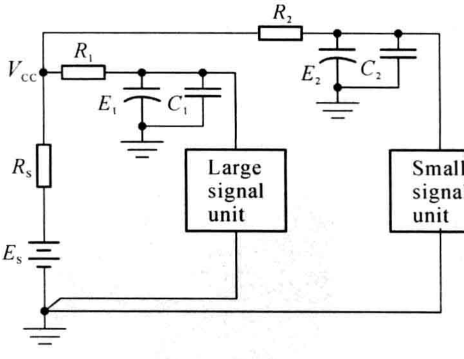

Figure 0 - 2 Illustration of dc power source de coupling and grounding path decoupling

There is also ground path coupling interference in the circuit system shown in Figure 0 - 1. An example of the grounding path decoupling configuration shown in

Figure 0 - 2 is known as "one point grounding". For the dc power source, the current through the grounding path back to its negative terminal is equal to the current from its positive terminal. The grounding path on a circuit board has resistance. Different units on the circuit board sharing a mutual grounding path can produce grounding path coupling. So, different units on the circuit board sharing a mutual grounding path must be avoided. There are more than ten units on the experimental board. Although all the grounds of the units are connected, the path and distance from each unit to the point of the dc power source are different. In an experiment, multi-point grounding, or grounding to other units could cause circuit output noise and/or interference to increase, and could even cause self-excitation. Taking Lab 4 as an example, the current of the power amplifier is larger than that of the voltage amplifier, and without "one point grounding" and "nearest grounding", self-excited oscillation will probably be caused by feedback due to grounding path coupling.

For an electronic circuit with several units, you must partition the board area to arrange the different units, and connect all the unit grounds at the ground of the dc power source, so as to achieve dc power supply decoupling and grounding path decoupling.

(2) Linear distortion caused by the circuit with limited pass-band width

Usually most of the signals are transient signals, such as voice signals, which have a certain bandwidth. If the pass-band of a linear circuit is wider than the bandwidth of the signal, and the circuit has linear phase, the output signal has no distortion. Otherwise, there will be distortion. The distortion caused by a circuit with limited pass-band width is called linear distortion. The narrower the pass-band of the circuit, the larger the overshoot and the longer the transition time of circuit step response.

For example, consider the circuit which is a second-order band-pass circuit with center frequency 1000 Hz, with an input of a 1000 Hz sine filled square wave. Figure 0 - 3 shows the output waveform of the circuit with $Q_p \approx 0.1$, which is almost the same as the input waveform. Figure 0 - 4 shows the output waveform of the circuit with $Q_p \approx 30$, which is obviously different from the input waveform. Usually, for circuit transient response, it is hoped that the transition time is short, and the overshoot is small, as shown in Figure 0 - 3.

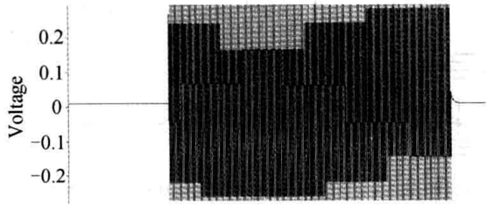

Figure 0 - 3 Output waveform when the circuit with $Q_p = 0.1$

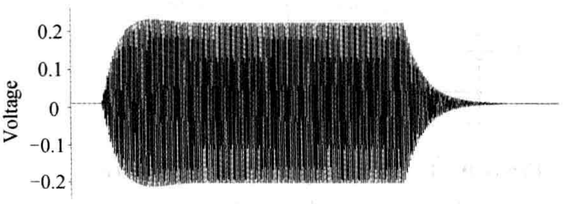

Figure 0 - 4 Output waveform when the circuit with $Q_p = 30$

(3) Nonlinear phase shift distortion

For a signal passing through a circuit, the output signal phase will lag the input signal phase. For a wideband signal through a circuit, only if the circuit phase frequency characteristic is linear, that is

$$\frac{d\theta(\omega)}{d\omega} = -\text{ constant.} \qquad (0-1)$$

Will the time delay of different frequency signal components through the circuit be the same, otherwise nonlinear phase shift distortion will occur. In equation (0 - 1), the $\theta(\omega)$ is the phase which is the function of angular frequency; "$-$" indicates that the circuit is a physical system in which output lags input.

Figure 0 - 5 shows the superposition of two signals, frequency: $f_1 = 6$ MHz, $f_2 =$ 18 MHz; amplitude: $V_1 = 3$ V, $V_2 = 1$ V; phase: $\theta_{10} = 0°$, $\theta_{20} = 0°$. Figure 0 - 6 is the superposition of two signals, phase: $\theta_1 = 0°$, $\theta_2 = 20°$, the frequency and amplitude are same as Figure 0 - 5. The figures show that the superimposed time domain waveforms with different phases are not the same. For output of the time domain waveform to be observed, distortion such as shown in Figure 0 - 6 is not allowed.

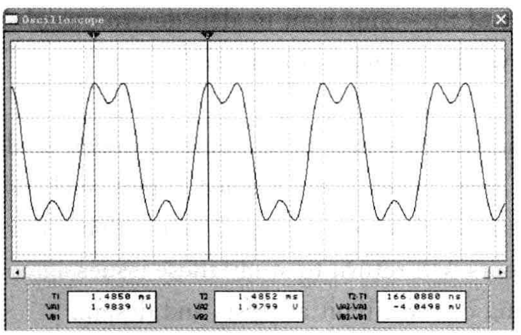

Figure 0 - 5 Simulation of superposition of two sine waves with same phase

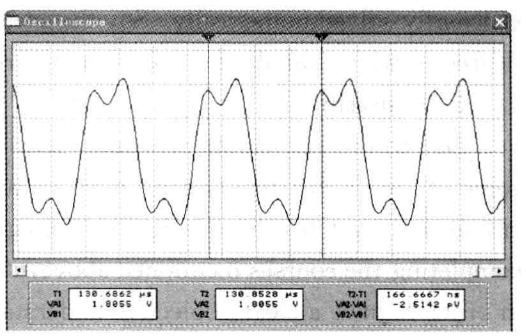

Figure 0 - 6 Simulation of superposition of two sine waves with phase shift

(4) Nonlinear amplitude distortion—harmonic distortion

Harmonic distortion is a common circuit nonlinear distortion.

If a circuit, with an input sine wave with period T, produces an output signal still of period T, but which is no longer a sine wave, then this phenomenon can be quantitatively described as harmonic distortion. Taking $x(t) = X_i \sin\omega_0 t$ as input, the output $y(t)$ can be represented as a Fourier series

$$\begin{aligned} y(t) &= \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + b_n \sin n\omega_0 t \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty} A_n \cos(n\omega_0 t - \varphi_n). \end{aligned} \qquad (0-2)$$

The second harmonic distortion and third harmonic distortion are defined as follows

$$d_3=\frac{A_3}{A_1}\times 100,\ d_2=\frac{A_2}{A_1}\times 100. \tag{0-3}$$

Thus total harmonic distortion of the signal is defined as

$$d=\frac{\sqrt{A_2^2+A_3^2+\cdots+A_n^2+\cdots}}{A_1}. \tag{0-4}$$

4. About computer circuit simulation

In this course, we use Electronics Workbench and Protel to do computer circuit simulation, both of which are SPICE-based software.

It must be noted that the circuit in a computer simulation is not a real circuit.

In simulation, each component in a circuit is represented by a mathematical model. Mathematical models link the schematic in the circuit window with the mathematical representation. The mathematical representation of a circuit is a set of simultaneous, nonlinear differential equations. The set of nonlinear differential equations is transformed into a set of nonlinear algebraic equations. These equations are further linearized to a set of linear algebraic equations. The set of linear algebraic equations is efficiently solved numerically. So, the accuracy of the component models determines the degree to which simulation results match real-world circuit performance.

5. Postscript

Due to the curriculum schedule, now some students may be not able to understand some of the issues mentioned above because they haven't yet studied topics such as circuit and system, linear algebra, integral transformations, etc. I hope that after completing the courses mentioned above, students will return to study these issues again in order to have a clear, objective understanding of the circuit analysis and design.

Analysis and design of circuits must be based on circuit and system theory, in which magnitude frequency characteristics and phase frequency characteristics of a circuit are very important, but are often ignored. Some people say analog circuit analysis and design mainly rely on practical experience, and the errors of the circuit can be smoothed away or even eliminated by adjustments based on experience. This statement is incorrect.

科技词汇

analog circuit	模拟电路
microelectronic	微电子的
oscilloscope	示波器
signal generator	信号源

dc power supply	直流电源
unit circuit	单元电路
physical dimension	物理量纲
simulation	仿真
printed circuit board(PCB)	印刷电路板
EWB(electronic workbench)	一种电路仿真软件的名称
Protel	一种电路分析设计制作软件的名称
electronic soldering iron	电子烙铁
datasheet	数据手册
ideal component	理想元件
nominal component	标称元件
real component	实际元件
parameter	参数
impedance	阻抗
aging characteristic	老化特性
common-mode rejection ratio(CMRR)	共模抑制比
resistance	电阻(值)
magnitude frequency characteristic	幅频特性
dynamic compression	动态压缩
interference	干扰
coupling	耦合
decoupling	去耦
ground	地,接地
self-excited oscillation	自激振荡
linear distortion	线性失真
pass band	通频带
bandwidth	带宽
band-pass circuit	带通电路
center frequency	中心频率
square wave	方波
waveform	波形
overshoot	超调量
phase frequency characteristic	相频特性
constant	常数
angular frequency	角频率
harmonic distortion	谐波失真
nonlinear distortion	非线性失真
nonlinear differential equation	非线性微分方程

nonlinear algebraic equation	非线性代数方程
linear algebraic equation	线性代数方程
magnitude frequency characteristics	幅频特性

注　释

1. Components shown in the analog circuit textbooks are mostly ideal components. You will choose suitable nominal components in circuit design. You will inevitably encounter real components in analog circuit experiments.

模拟电路教科书中的元件几乎都是理想元件。在电路设计中，你将选择适合的标称元件。在模拟电路实验中，你将不可避免地遇到实际元件。

2. The real resistance value of the resistor is usually similar to the nominal value of the resistor, but not exactly equal to the nominal value.

实际电阻的电阻值通常与该电阻的标称值差不多，但并不严格等于标称值。

3. A performance parameter in the datasheet of a nominal op-amp is often given minimum, typical, and maximum values; this shows that the performance parameters of real op-amp with same type may be different from each other, but should be within the performance parameter range of the nominal op-amp.

数据手册中标称运放的性能参数常常给出最小值、典型值、最大值，这表明同型号实际运放的性能参数相互之间有可能不同，但应该在标称运放性能参数的范围之内。

4. Taking real component performance parameters into account, using the theory of linear systems to analyze the experimental circuit, allow results obtained by the analysis to often correspond quite closely with the real measured results.

计及实际元件的性能参数，用线性系统理论分析实验电路，可使由分析得到的结果与实际测量的结果非常接近。

5. Different units on the circuit board sharing a mutual grounding path can produce grounding path coupling. So, different units on the circuit board sharing a mutual grounding path must be avoided.

在电路板上不同单元共用地线可引起地线耦合。因此，必须避免电路板上不同单元共用地线。

6. The narrower the pass-band of the circuit, the larger the overshoot and the longer the transition time of circuit step response.

电路的通带越窄，则电路阶跃响应的超调量越大，过渡过程时间越长。

7. Will the time delay of different frequency signal components through the circuit be the same, otherwise nonlinear phase shift distortion will occur.

必须使不同频率的信号分量通过电路的时延相同，否则将发生非线性相移失真。

8. In simulation, each component in a circuit is represented by a mathematical model. Mathematical models link the schematic in the circuit window with the

mathematical representation. The mathematical representation of a circuit is a set of simultaneous, nonlinear differential equations. The set of nonlinear differential equations is transformed into a set of nonlinear algebraic equations. These equations are further linearized to a set of linear algebraic equations. The set of linear algebraic equations is efficiently solved numerically. So, the accuracy of the component models determines the degree to which simulation results match real-world circuit performance.

在仿真中,每一个元件由其数学模型表示。这些数学模型以数学表达式与电路窗口中电路原理图相联系。电路的数学表达式是联立的非线性微分方程组。非线性微分方程组被转化为非线性代数方程组。该方程组进一步被线性化为线性代数方程组。线性代数方程组被高效地求得数值解。因此,元件模型的精度决定了仿真结果与实际电路性能相似的程度。

Lab 1 Common-Emitter Voltage Amplifier

实验一 共射极电压放大器

Purpose

❶ Learn to use electronic instruments to measure parameters of electronic circuits.

❷ Learn the method of adjusting the quiescent operating point (simplified as Q-point) of the common-emitter voltage amplifier.

❸ Measure the forward current gain coefficient of a BJT, the voltage gain, Bode plot, the harmonic distortion, the input resistance and the output resistance of the common-emitter voltage amplifier.

Pre-lab

❶ Be familiar with the working principle of the common-emitter voltage amplifier.

❷ Set the Q-point, calculating voltage gain, input and output resistances of the common-emitter voltage amplifier.

❸ Study the method of measuring the magnitude frequency characteristic curve and nonlinear harmonic distortion of the amplifier.

Apparatus

Dual trace oscilloscope;
Signal generator;
Digital multimeter(DMM).

Introduction

The experimental circuit is a common-emitter voltage amplifier as shown in Figure 1-1. The resistor divider is consisted of R_{b1}, R_p and R_{b2} which biases the base of the transistor. The emitter resistors (R_{e1}, R_{e2}) construct the dc series-series negative feedback biasing. Because of it the temperature stability of Q-point of the amplifier is improved.