Implementation of a Function Generator

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May 2012

Bachelor’s Thesis in Electronics

Bachelor’s Program in Electronics/Telecommunications
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Preface

The authors would like to show the deepest gratitude to the supervisor Mr. Mohamed Hamid for his professional guide and supervision. With his help, we could finish our thesis work.
Abstract

Function generator has been widely used in each electronics fields recent years. In this thesis, the authors will introduce some basic structure and working principles of a function generator, moreover a function generator which can create three kinds of wave: sine wave, square wave and triangle wave has been implemented. There are many ways to build the function generator; a method of combine the operational amplifier and discrete components is introduced in this thesis. First use the RC Wien bridge oscillator to achieve sinusoidal wave; and convert it into square wave by using the shaping circuit. Lastly, use the integrating circuit to obtain triangle wave. The basic simulation software Multisim has been used to simulate the circuit.

Key words: Function generator, Sine-wave, Square-wave, Triangle-wave.
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1 Introduction

1.1 Background

Today's electronic systems require many signal waveform shapes. Common waveforms are the square wave, triangular wave, and single pulse wave with fixed duration. Fixed duration pulses are used in communication and control systems. Square waves are used as a clock for digital systems. Triangular waves are used for scanning an electron beam on a CRT screen, in precise time measurements, and in time modulation [1]. With the development of modern technology, the function generator with independent control of amplitude and frequency play an important role in applied electronics, communications, instrumentation and signal processing applications [2].

The function generator is a measurement equipment with long history, it has been produced in 1920. With the development of communication technique and radar technique, in 1940, the function generator used to test standard signal of various receiver appeared, this improvement change the function generator from a qualitative investigation testing instrument to a quantitative analysis measuring instruments. At the same time, the pulse function generator to measure the pulse circuit or modulate the pulse has been made. The mechanical structure of the function generator is very complex in early time, which led the slowly evolution of the function generator. Till 1964, the first function generators with whole transistors were created.

As a common used signal source, function generator is the most extensive used of general instrument in the modern test area. To research, production, testing and maintenance each electronic components, units and the machine equipment, the signal source are needed. It produces voltage signal and current signal with different frequency and wave form, and added to the device or equipment which being measured, then observe and measuring the output response of the measured instrument to analyze and identify their performance parameters. Function generator is the most basic and widely used electronic instruments in electronic measurement field. It has not only been applied in the domains of education, scientific research, production and engineering, but also have some advantages such as continuous phase transformation, frequency stabilization and so on; it is useful in simulate various complex signal and dynamic control the values, such as frequency, amplitude, phase and wave form; the function generator can also communicate with other equipments to constitute automatic test system (ATS), so it can also applied in the domains of communication, ATS, instrument and meter.
1.2 Wave generator architectures

In the modern field of electronic systems, wave generator can be used as stand-alone signal sources or may be a part of integrated sensing system for providing excitation and control. Tuning of amplitude and frequency and independent control adds extra flexibility to the system and required in many sensor based integrated system applications like the micro-machined resistive and capacitive sensors [3]. In this part, different kinds of wave generator and its applications will be introduced.

1.2.1 Square-wave Generator

The square-wave generator with amplitude and frequency tuning has been shown is Figure 1-1. Operational Transconductance Amplifier (OTA) has been used in it. OTA-2 and OAT-3 along with resistors R1 and R2 are configured as voltage amplifiers which are connected in positive feedback, from a Schmitt trigger. OTA-1 along with the capacitor C forms an integrator which determines the frequency of the square wave depending on its time constant. OTA-4 with resistor R3 provides the out phase output of the square-wave. The amplitude of the square-waves depends on the bias currents of OTA-2 and OTA-4(Ib2 and Ib4) and also R1 and R3.

This generator is suitable for integrated capacitive and resistive sensors and other instrumentation applications.
1.2.2 Triangular/Square-Wave Generator

A triangular/square-wave generator in which the frequency and amplitude of the square waveform can be independently and linearly controlled by dc bias currents has been illustrated in Figure 1-2. Two voltage amplifiers (one is composed of OTA₁ and R₁ and the other OTA₂ and R₂) connected in a positive-feedback manner form a Schmitt trigger. OTA₃ and the timing capacitor C form an integrator. The frequency of the waveform is directly proportional to the I₉₃, whereas the amplitude is directly proportional to the I₉₁.

On the one hand, the application of the circuit to a current-controllable saw-tooth waveform generator is also presented. On the other hand, it has a wide range of applications in instrumentation and measurement systems.

1.2.3 Sinusoidal/Triangular/Square-wave generator

The Figure 1-3 shows a function generator, which can generate sinusoidal, triangular and square wave. Operating principle: 555 timer and some components constitute a multivibrator. C₂ is a timing capacitor, its charge circuit is R₂→R₃→RP→C₂ and its discharge circuit is C₂→RP→R₃→Pin7(discharge tube). Because R₃+RP >> R₂, charge time constant approximately equal to discharge time constant, pin 3 generate approximate symmetry square wave. As component parameters in the Figure 1-3, its frequency is 1kHz, and it can change the oscillator frequency to adjust potentiometer RP. Through R₄ and C₅ integrating circuit, generate triangle wave. The triangle wave pass through R₅ and
C_6 integrating circuit again, generate approximate symmetry sine wave. C_2 is power filter capacitor. The light-emitting diode VD is a power light.

![Diagram of a function generator](image)

**Figure 1-3, Diagram of a function generator**

### 1.2.4 Arbitrary Waveform Generator

There are many kinds of methods of designing arbitrary waveform, and they are based around digital techniques, but the two main categories always fall into their design.

#### 1.2.4.1 Arbitrary function generator

This type is based on the direct digital synthesis techniques (DDS) and uses integrated circuits to be created relatively and for an economic price.

Figure 1-4 shows the operation of a direct digital synthesizer. It operates by storing the points of a wave in digital format in a memory to recall them to generate the wave. The points can be any form of repetitive waveform, which is required. The rate of the DDS completes one wave decide the frequency.

![Block diagram of arbitrary function generator](image)

**Figure 1-4, Block diagram of arbitrary function generator [6]**

Figure 1-5 shows the phase advances around the circle corresponds to advances in the wave. From it, it can be obtain the faster we complete the cycles, the higher we can achieve the frequency of the wave.
This arbitrary function generator has many advantages, such as digital and sub-hertz frequency resolution. There is also some disadvantage, which should also be taken into account. For example, it can generator any kinds of wave, but the wave sequencing is not possible using DDS arbitrary function generator.

**1.2.4.2 Variable clock arbitrary waveform generator**

The variable clock arbitrary waveform generator is more complex to use and also more expensive, so it not may always be the most economic instrument.

It uses variable frequency clocks to access points on a waveform stored in RAM, and then convert into an analogue format. The number of that wave points govern the clock frequency, which is the recestition frequency. Furthermore the variable clock arbitrary waveform generator include several techniques such as memory segmentation and sequencing whose function is to improve the capabilities of this arbitrary generator. Its block diagram is illustrated in Figure 1-6.

As amentioned, it is costly and more complicated set-up, but it also has advantage such as it can produce the widest variation fo waveforms of any form of generator and also link several waveforms together within the memory.
Nowadays, the various function generators are produced by some companies. The Agilent and B&K precision are very famous companies in this field. They build various function generators.

1.3 **Aim**

1.3.1 **Original opinion**

The original opinion is a programmable function generator, which can obtain different kinds of waveform by using different binary input signals, but our laboratory room cannot provide that components needed in the programmable function generator, so the thesis work must need some change. If Laboratory Equipment conditions permitted in the future, that is possible to let this research better.

1.3.2 **Final opinion**

The main object of this thesis is to build a function generator which is the breadboard circuit based on the operational amplifier and diodes, capacitors, resistors and can achieve three kinds of common waveform. In this paper, a new scheme is presented in which the frequency of the waveform can be controlled by changing resistance and capacitance. First we will learn to understand the working principle and architecture of sinusoidal –wave generator, square-wave generator and triangular-wave generator, and then simulation of a function generator will be created by Multisim. Finally combine the three types of waveforms to build up a function generator.

In this paper, following this introductory section, its configuration and principles of operations are given in the basic theory section. Some experimental results and product model are presented in subsequent sections.
2 Theory

2.1 Sinusoidal-wave generator

The sinusoidal oscillator is one of the classical applications of op-amp based active circuits [7]. Canonic sinusoidal oscillators are designed with two capacitors, four resistors, and only one op-amp [8], that is Wien-Bridge Oscillator.

2.1.1 Canonic sinusoidal oscillator

Figure 2-1 shows a basic Wien-Bridge Oscillator. It generates an oscillatory output signal without having any input source and has widely applied in low frequency oscillating circuit. Uses two RC networks connected to the positive terminal to form a frequency selective feedback network and cause oscillations to occur. Amplifies the signal by the two negative feedback resistors.

Figure 2-1, Basic Wien-Bridge Oscillator

The loop gain can be found by doing a voltage division from the Figure 2-2.

\[ V_o(s) = V_i(s) \cdot \frac{z_2(s)}{z_1(s) + z_2(s)} \quad (2-1) \]
The two RC networks must equal resistor and capacitors

\[ Z_1(s) = R + \frac{1}{s \cdot C} \quad (2-2) \]

\[ Z_2(s) = \frac{R \cdot \frac{1}{s \cdot C}}{R + \frac{1}{s \cdot C}} \quad (2-3) \]

Need to find the Gain over the whole circuit: \( \frac{V_O}{V_S} \)

Operational amplifier gain

\[ G = \frac{V_1(s)}{V_S(s)} = 1 + \frac{R_2}{R_1} \quad (2-4) \]

\[ V_O(s) = V_1(s) \cdot \frac{Z_2(s)}{Z_1(s) + Z_2(s)} \quad (2-5) \]

Solve \( G \) equation for \( V_I \) and substitute in for above equation

\[ V_O(s) = G \cdot V_S(s) \cdot \frac{s \cdot R \cdot C}{s^2 \cdot R^2 \cdot C^2 + 3 \cdot R \cdot C + 1} \quad (2-6) \]

We now have an equation for the overall circuit gain

\[ T(s) = \frac{V_O(s)}{V_S(s)} = \frac{s \cdot R \cdot C \cdot G}{s^2 \cdot R^2 \cdot C^2 + 3 \cdot R \cdot C + 1} \quad (2-7) \]

Simplifying and substituting \( j\omega \) for \( s \)

\[ T(j\omega) = \frac{j \cdot \omega \cdot R \cdot C \cdot G}{(1 - \omega^2 \cdot R^2 \cdot C^2) + 3 \cdot j \cdot \omega \cdot R \cdot C} \quad (2-8) \]
In order to have a phase shift of zero,

\[ 1 - \omega^2 \cdot R^2 \cdot C^2 = 0 \]  \hspace{1cm} (2-9)

This happens at \( \omega = \frac{1}{RC} \).

When \( \omega = \frac{1}{RC} \), \( T(j\omega) \) simplifies to:

\[ T(j\omega) = \frac{G}{3} \]  \hspace{1cm} (2-10)

If \( G = 3 \), oscillations occur.

If \( G < 3 \), oscillations attenuate.

If \( G > 3 \), oscillations amplify.

2.1.2 Frequency conversion

The analysis for Wien-Bridge Oscillator is shown in Figure 2-6. It uses a feedback circuit consisting of a series RC circuit connected with a parallel RC of the same component values producing a phase...
delay or phase advance circuit depending upon the frequency. At the resonant frequency $f_r$, the phase shift is $0^\circ$.

![Diagram of Wien Bridge Oscillator](image)

**Figure 2-6, Analysis for Wien-Bridge Oscillator**

The frequency of oscillations for a Wien Bridge Oscillator is given as:

$$f_r = \frac{1}{2\pi RC} \quad (2-11)$$

Where:
- $f_r$ is the Resonant Frequency in Hertz
- $R$ is the Resistance in Ohms
- $C$ is the Capacitance in Farads

In this paper, in order to change the frequency, the chosen method is to entrust a constant for the resistor and change the capacitance. The example 2-1 shows the changing of the frequency.

**Example 2-1:** Determine the maximum and minimum frequency of oscillations of a Wien-Bridge Oscillator circuit having a resistor of $10k\Omega$ and a variable capacitor of $1nF$ to $1000nF$.

**Lowest Frequency**

$$f_{\text{min}} = \frac{1}{2\pi(10K\Omega) \times (1000 \times 10^n)} = 15.9 \text{ Hz}$$

**Highest Frequency**

$$f_{\text{max}} = \frac{1}{2\pi(10K\Omega) \times (1 \times 10^n)} = 15,915 \text{ Hz}$$

This kind of sinusoidal oscillator based on Wien-Bridge Oscillator circuit will be mended and apply to this research.
2.2 Square-wave generator

Since the anode of the zener is connected to the inverting (-) input, it is a virtual ground (\( \equiv 0V \)). Therefore, when the output voltage reaches a positive value equal to the zener voltage, it limits at that value, as illustrated in Figure 2-7(a). When the output switches negative. The zener acts as a regular diode and becomes forward-biased at 0.7 V, limiting the negative output voltage to this value. As shown in part (b). Turning the zener around limits the output voltage in the opposite direction.

![Figure 2-7, Operation of a bounded comparator [9]](image)

Two zener diodes arranged as in Figure 2-8 limits the output voltage to the zener voltage plus the forward voltage drop (0.7V) of the forward-biased zener, both positively and negatively, as shown.

![Figure 2-8, Double-bounded comparator [9]](image)

That will be improved and used in this paper to generator square waveform.
2.3 Triangular-wave generator

2.3.1 The integrator current

In Figure 2-9, the inverting input of the op-amp is at virtual ground (0V), so the voltage across $R_i$ equals $V_{in}$. Hence, the input current is

$$I_{in} = \frac{V_{in}}{R_i} \quad (2-12)$$

![Figure 2-9, Current in an integrator][9]

If $V_{in}$ is a constant voltage, then $I_{in}$ is also a constant because the inverting input always remains at 0V, keeping a constant voltage across $R_i$. Because of the very high input impedance of the op-amp, there is negligible current at the inverting input. This makes all of the input current go through the capacitor, as indicated in Figure 2-9, so

$$I_C = I_{in} \quad (2-13)$$

2.3.2 The capacitor voltage

Since $I_{in}$ is constant, so is $I_C$. The constant $I_C$ charges the capacitor linearly and produces a linear voltage across $C$. The positive side of the capacitor is held at 0 V by the virtual ground of the op-amp. The voltage on the negative side of the capacitor, which is the op-amp output voltage, decreases linearly from zero as the capacitor charges, as shown in Figure 2-10.

![Figure 2-10, Voltage in an integrator][9]
2.3.3 The output voltage

$V_{out}$ is the same as the voltage on the negative side of the capacitor. When a constant positive input voltage in the form of a step or pulse (a pulse has a constant amplitude when high) is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level. This is indicated in Figure 2-11.

![Diagram](image-url)

Figure 2-11, An op-amp integrator [9]

Integrator is useful in triangular-wave oscillators as you will see in this paper.

In this section, a new scheme of RC-active Wien bridge oscillator is proposed, whose oscillation frequency is quite independent on the time constants of the op-amps used in the design, and is determined by passive components.

2.4 Evolution

2.4.1 Improved Sine-wave generator

2.4.1.1 Oscillation balance condition

To make the output signal of oscillator $\dot{X}_o$ stable, the feedback signal to the input end $\dot{X}_f$ should equal to the initialize signal $\dot{X}_i$, which is $\dot{X}_f = \dot{X}_i$

And

$$A = \frac{X_o}{X_i}, \quad F = \frac{\dot{X}_f}{X_o}$$

(2-14)

Where the $A$ is the amplitude,
$F$ is the frequency.

Then

$$\dot{X}_f = AF \dot{X}_i$$

(2-15)

Because of $\dot{X}_f = \dot{X}_i$
So the condition of oscillating is:

\[ AF = 1 \]

If \( A = A \angle \varphi_a \), \( F = F \angle \varphi_f \),

Then \[ AF = AF \angle (\varphi_a + \varphi_f) = 1 \] ; \hfill (2-16)

We get:

\( AF = 1 \) is the condition of amplitude balance;

\( \varphi_a + \varphi_f = 2n\pi (n=0,1,2\ldots) \) is the condition of phase balance.

To be oscillating, the oscillator has to fulfill the two conditions above.

### 2.4.1.2 Start-up conditions

When the oscillator content the balance condition, the amplitude of output signal \( X_f = X_i \) doesn’t change. At the beginning of oscillating, the signal is very weak, the oscillator will not oscillating if \( X_f = X_i \). The feedback signal needs to be larger than the initial input signal, which is \( X_f \cdot X_i \).

Then the oscillating can be built more and more stranger.

Here is the oscillation initial condition \( AF > 1 \).

### 2.4.1.3 Improved RC Wien’s bridge oscillator

As the circuit of RC Wien’s bridge oscillator have a variable frequency, and it’s easy to connect and oscillate. In this thesis, an improved canonic sinusoidal oscillator is shown in the Figure 2-12. In order to test this generator, that components must be given a constant like displayed on the Figure 2-12.

Compare with canonical sinusoidal oscillator, this improved circuit better than the canonical circuit, because the two diodes D1 and D2 can keep circuit around \( G = 3 \) and achieve perfect waveform. If \( G = 3 \), diodes are off. When output voltage is positive, D1 turns on and R6 is switched in parallel causing G to drop. When output voltage is negative, D2 turns on and R6 is switched in parallel causing G to drop. Add a potentiometer R4 to specify signal expediently.

Turn on the power supply, it include many AC harmonic wave because of the current of the circuit changed from zero to a value. the signal with frequency \( f_0 \) which selected by frequency-selective function positive feedback network, on one hand the signal will output by the output end, on the other hand the signal will be sent to the input end by positive feedback network, by constantly repeat.
amplification and frequency-selecting, round and round, as long as the feedback signal is stronger than initializing signal, the oscillating will take place.

![Figure 2-12, The improved structure of the Sine-wave generator](image)

**2.4.2 Improved Square-Triangle wave generator**

The Figure 2-13 shows an improved square-triangle wave generator. That uses the voltage comparators and integrator to build a square wave and triangle wave. The voltage comparators create the square wave and integrate the output square wave, the triangle wave will be built. For this circuit, the linearity and stability are nicer, and the frequency is easy to adjust, but the amplitude is unable changing.

In the square-wave section, add resistor as protective resistor and reduce noise by using hysteresis. In the triangular-wave section, add a potentiometer R10 to easily adjust the rate of change of the triangular-wave output.
To sum up, use a RC Wien Bridge to generate sinusoidal-wave, use a comparator to achieve square-wave, and use an integrating circuit to obtain triangular-wave.
3 Software and Modeling Testing

From what has been discussed in the theory section, a diagramatic drawing of function generanor can be structured, shown in Figure 3-1.

![Diagrammatic drawing of function generator](image)

Figure 3-1, Diagrammatic drawing of function generator

3.1 Software testing

With Multisim, you can optimize your circuit design performance with powerful SPICE simulation and intuitive analyses. You can reduce design errors, prototype faster, and improve productivity. Save prototype iterations and optimize printed circuit board (PCB) designs earlier in the design process by using the Multisim design approach. The Multisim software has the ability to simulate function generator and help us collect data.

The proposed design of the function generator is shown in Figure 3-2 by using Multisim software. The design contains three part like illustrated in Figure 3-1, and that can obtain three kinds of waveform with different frequency. The testing result will be shown in the results section.

![The main circuit of function generator](image)

Figure 3-2, The main circuit of function generator
3.2 Modeling Testing

From the Figure 3-2, a correct method to build a function generator has been approved. Use the components provided in the Appendix B to build a function generator model. After assembling all of the components, it is necessary to debug the model by using an oscilloscope. Finally, the model can generate sinusoidal-wave, square-wave, and triangular-wave and has shown in Figure 3-3. Waveform generated by the model will be presented in the results section.
4 Results and Evaluation

In this Chapter, different kinds of waveform with different frequency will be illustrated. In order to show the model can change frequency, the capacitance of C1, C2 have been changed. In consideration of easy to find in our laboratory, the following components have been chose to change the frequency.

<table>
<thead>
<tr>
<th>C1 = C2</th>
<th>100nF</th>
<th>220nF</th>
<th>330nF</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>106 Hz</td>
<td>48Hz</td>
<td>32Hz</td>
</tr>
</tbody>
</table>

Table 4-1, theoretical calculation

4.1 Results

4.1.1 From the Multisim testing

Simulate the function generator in the Multisim by using Figure 3-2, after that preserve the resistance R1 and R2, but change the capacitance of C1 and C2 to achieve different frequency for the output signals.

Figure 4-1, Sinusoidal waves created by Multisim
Figure 4-2, Square waves created by Multisim

Figure 4-3, Triangular waves created by Multisim
4.1.2 From the model testing

Connect the model with an oscilloscope and a DC power supply, and then give the three OP-AMP a DC voltage ±15V. Finally, use the difference capacitance to observe the different frequency of waveform by an oscilloscope. After finished the above steps, the following wave forms were achieved.

![Figure 4-4, Sinusoidal waves shown on the oscillator](image)

Figure 4-4, Sinusoidal waves shown on the oscillator
Figure 4-5, Triangle waves shown on the oscillator

Figure 4-6, Triangle waves shown on the oscillator
4.2 Evaluation

This function generator generates the three kinds of waveform with different frequency. The performance of the simulated function generator agrees with the function of the mould. But this function generator cannot change the waveform amplitude. To sum up, it can achieve expected goals, but not perfect, so it still can be improved in the future.
5 Conclusion and Discussion

In this thesis, a function generator has been achieved. Three kinds of waveforms have been generated by simulating the function generator and debugging the model of the function generator. Also the frequency of the each kind wave can be changed by changing the resistance and capacitance, but the amplitude of the waveforms is unable to change.

It has the following advantages. It can produce a sinusoidal output and without other help. The mould of the function generator can be constructed on a bread board, so it facilitates us in learning and help us learn more about function generator. Nothing is perfect, so it also has a few of disadvantages. If the square wave and triangle wave wants to be achieved, above all obtain sinusoidal; if not, there is nothing observed for this function generator. External conditions such as connection problem easily interfere with the process of the function generator.

In this study, use RC Wien bridge oscillator to achieve sinusoidal wave; use the comparator circuit to convert sinusoidal wave into square wave; use the integrating circuit to obtain triangle wave. It is one of the useful models to help us to learn more about function generator. This kind of function generator has been chosen as our study. The reasons for this are as follows. To begin with, this system is independence, which means that the system needs not to apply on an input signal or voltage. The system can directly achieve wave form without other conditions. Moreover, the circuit of the function generator is not complicated and easy to understand. Lastly, these electronic components employed in the model are so easy to find in our laboratory and then the model can easily be constructed. So this method has been employed in our study.

Multisim is equipped with a database of as many as 22,000 components from leading semiconductor manufacturers such as Analog Devices, National Semiconductor, NXP, ON Semiconductor, and Texas Instruments. Choose from a comprehensive list of up-to-date amplifiers, diodes, transistors, switch mode power supplies, and other components to rapidly design and evaluate analog and digital circuits [10]. So when use the Multisim to simulate the function generator, it is possible to find all components. But in our laboratory, that is not possible, sometime it is necessary to change.

To sum up, in the simulation, the three kind of wave form successfully achieved, so a correct way to construct a function generator was employed, but if need other kind of wave form, that is not possible. In the future, further research will have to improve it. In our laboratory, the main circuit was built in a bread board and performance has been verified by the oscilloscope and in our future, plenty of this
kind of function generator can be produced to let students learn more about the structure of a function generator. For the future work, the project can focus on how to change the amplitude for the waveform, and more kinds of waveform can be added in the function generator. And the framework of the circuit can be improved, to make it more embellish, the circuit can be soldering on the circuit board. Then the whole system of the function generator will be more distinct and perfect.
6 References


## Appendix A: The components used in the circuit

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>15kΩ</td>
</tr>
<tr>
<td>R2</td>
<td>15kΩ</td>
</tr>
<tr>
<td>R3</td>
<td>330Ω</td>
</tr>
<tr>
<td>R4</td>
<td>100kΩ</td>
</tr>
<tr>
<td>R5</td>
<td>15kΩ</td>
</tr>
<tr>
<td>R6</td>
<td>100kΩ</td>
</tr>
<tr>
<td>R7</td>
<td>15kΩ</td>
</tr>
<tr>
<td>R8</td>
<td>330Ω</td>
</tr>
<tr>
<td>R9</td>
<td>50kΩ</td>
</tr>
<tr>
<td>R10</td>
<td>1MΩ</td>
</tr>
<tr>
<td>R11</td>
<td>10kΩ</td>
</tr>
<tr>
<td>C1</td>
<td>220nF</td>
</tr>
<tr>
<td>C2</td>
<td>220nF</td>
</tr>
<tr>
<td>C3</td>
<td>50nF</td>
</tr>
<tr>
<td>VCC</td>
<td>15V</td>
</tr>
<tr>
<td>VEE</td>
<td>-15V</td>
</tr>
<tr>
<td>OP-Amp 1</td>
<td>741</td>
</tr>
<tr>
<td>OP-Amp 2</td>
<td>741</td>
</tr>
<tr>
<td>OP-Amp 3</td>
<td>LM741cn</td>
</tr>
<tr>
<td>D1</td>
<td>1N4148</td>
</tr>
<tr>
<td>D2</td>
<td>1N4148</td>
</tr>
<tr>
<td>D3</td>
<td>1N4148</td>
</tr>
<tr>
<td>D4</td>
<td>1N4148</td>
</tr>
</tbody>
</table>

Where:
- R = resistance
- C = capacitance
- V = voltage
- D = diode
- Op-Amp = operation amplifier
Appendix B: Data sheet for operational amplifier 741

Connection Diagrams

Dual-In-Line or S.O. Package

Offset Nulling Circuit
### Specifications of used operation amplifiers

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

<table>
<thead>
<tr>
<th></th>
<th>LM741A</th>
<th>LM741</th>
<th>LLM741C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>± 22V</td>
<td>± 22V</td>
<td>± 18V</td>
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<tr>
<td>Power Dissipation (Note 3)</td>
<td>500 mW</td>
<td>500 mW</td>
<td>500 mW</td>
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<tr>
<td>Differential Input Voltage</td>
<td>± 30V</td>
<td>± 30V</td>
<td>± 30V</td>
</tr>
<tr>
<td>Input Voltage (Note 4)</td>
<td>± 15V</td>
<td>± 15V</td>
<td>± 15V</td>
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<tr>
<td>Output Short Circuit Duration</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>−55˚C to +125˚C</td>
<td>−55˚C to +125˚C</td>
<td>0˚C to +70˚C</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>−65˚C to +150˚C</td>
<td>−65˚C to +150˚C</td>
<td>−65˚C to +150˚C</td>
</tr>
<tr>
<td>Junction Temperature</td>
<td>150˚C</td>
<td>150˚C</td>
<td>100˚C</td>
</tr>
<tr>
<td>Soldering Information</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-Package (10 seconds)</td>
<td>260˚C</td>
<td>260˚C</td>
<td>260˚C</td>
</tr>
<tr>
<td>J- or H-Package (10 seconds)</td>
<td>300˚C</td>
<td>300˚C</td>
<td>300˚C</td>
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<tr>
<td>M-Package</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor Phase (60 seconds)</td>
<td>215˚C</td>
<td>215˚C</td>
<td>215˚C</td>
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<tr>
<td>Infrared (15 seconds)</td>
<td>215˚C</td>
<td>215˚C</td>
<td>215˚C</td>
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<tr>
<td>Surface mounts devices.</td>
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<td></td>
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<tr>
<td>ESD Tolerance (Note 8)</td>
<td>400V</td>
<td>400V</td>
<td>400V</td>
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</tbody>
</table>