RCET 2253 Instructions

Systems Analog & Digital Laboratory

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Timothy S. Leishman

Clinical Assistant Professor

College of Technology

Idaho State University

Contents

Introduction

Hello and welcome,

My name is Tim Leishman, and I am thrilled to be a part of the dynamic world of the College of Technology at Idaho State University. As an Assistant Professor in the Robotics and Communications Systems Technology program, I find my purpose at the intersection of education and technology.

With a deep-rooted passion for electronics, particularly the intricate and diverse world of transistors, my journey has been an exciting exploration of knowledge and innovation. My goal? To inspire, support, and connect with individuals like you – students who are curious, driven, and excited about the possibilities that the world of electronics offers.

I started my teaching career in 2013, and since then I've been preparing students for rewarding and in-demand careers in the field of electronics. As you step into this semester, my mission is to guide you not only in mastering electronics but also in developing qualities like self-discipline and a positive mental attitude that are invaluable in any journey.

Before teaching, I gained valuable experience as a Certified Biomedical Equipment Technician at Providence St. Vincent Medical Center, I was able to hone my troubleshooting skills in the world of Test and Measurement at Tektronix, and I proudly served in the United States Air Force, where I managed visual imagery and intrusion detection systems. My diverse background has given me a holistic perspective that I bring to the classroom – a perspective that resonates with the challenges and opportunities you'll encounter.

As you embark on your journey into the realm of electronics, remember that I'm here to accompany you every step of the way. Whether you're deeply passionate about electronics, intrigued by the wonders of STEM, or searching for an enriching learning atmosphere, I'm here to establish a connection, exchange insights, and help lead you toward your goals.

Together, we'll uncover the potential that lies within you. I invite you to be a part of this exciting journey of growth, learning, and discovery.

Warm regards,

Tim Leishman

Laboratory Rules

0.1 Safety Rules

Lab safety is a crucial aspect of any laboratory environment, whether it's in a school, research facility, or industrial setting. Proper lab safety practices help prevent accidents, injuries, and exposure to potential hazards. Here are some key principles and guidelines for lab safety:

0.1.1 Key Safety Principles:

1. **Personal Protective Equipment (PPE):**
    - Wear appropriate safety glasses and closed-toed shoes at all times while in the Lab.
2. **Emergency Preparedness:**
    - Familiarize yourself with emergency procedures, including evacuation plans.
    - Know the location of the eye wash and First Aid Kit.
3. **Electrical Safety:**
    - Do not energize or de-energize an electrical breaker or electrical switch that you have not been given specific authorization to operate, except in the case of an emergency safety situation.
    - Observe lock-out/tag-out procedures at all times.
    - Know how to switch off bench power.
4. **Fire Safety:**
    - Know the location of fire extinguishers and emergency exits.
    - Avoid open flames in areas where flammable materials are present.
5. **Safety Training:**
    - Receive proper training before working in the lab.
    - Stay up-to-date with safety protocols.

6. **Risk Assessment:**

   - Thoroughly understand experimental procedures before starting.
   - Identify potential hazards and determine how to minimize them.

7. **Equipment Handling:**

   - Follow operating instructions for equipment.
   - Regularly inspect equipment for damage or malfunctions.

8. **Lab Cleanliness:**

   - Keep workspaces clean and uncluttered.
   - Dispose of waste materials properly, following appropriate waste disposal procedures.

9. **Chemical Handling and Storage:**

   - Store chemicals in properly labeled containers, away from incompatible substances.
   - Keep chemicals away from direct sunlight or heat sources.

10. **Hazard Communication:**

    - Clearly label all chemicals and hazardous materials.
    - Use Material Safety Data Sheets (MSDS) to understand the hazards associated with chemicals.

11. **Personal Hygiene:**

    - Wash hands thoroughly after working with chemicals, solder, or contaminated materials.
    - Avoid eating, drinking, or applying cosmetics in the lab.

12. **Supervision and Communication:**

    - Never work alone in a laboratory when potential hazards are present.
    - Communicate any concerns or incidents to supervisors or lab managers.

Lab safety is a shared responsibility. Everyone working in the lab should be aware of and committed to safety protocols in order to create a safe working environment.

0.2 General Rules

0.2.1 Respectful Conduct

Respecting others, including fellow students, instructors, and lab assistants, is vital for maintaining a productive and positive learning environment.

- Respect your fellow students by collaborating and communicating kindly. Support each other's learning efforts.
- Show respect to instructors by being attentive and following their guidance.
- Appreciate the role of lab assistants and follow their instructions for a smooth lab experience.
- Communicate with patience and respect, embracing diversity and fostering inclusivity.
- Take personal responsibility for your actions and their impact on others. Rectify mistakes responsibly.

Fostering respect enhances the overall learning experience for everyone involved.

0.2.2 Food and Beverages

Please confine all food and beverage items to the designated area. It is the responsibility of students to maintain cleanliness in the food and drink areas. Any items left in these areas will be disposed of every evening. Failure to comply with these rules will result in the removal of access to these designated areas.

0.2.3 Clear Pathways and Work Areas

Maintain the walkways free from obstacles, backpacks, and debris. Prior to leaving the lab, ensure your workspace is neat and your lab bench is clean. If you utilize any common work areas, kindly tidy up after yourself and return any borrowed tools. It's important to remember that the lab may occasionally be visited by individuals observing both your work and the lab's condition. Keep your work area and the floors tidy, as these visitors might include potential future employers.

- Perform a quick cleanup at the conclusion of each experiment. Return components, lab manuals, special test equipment, and leads to their designated places.
- Only keep the necessary assigned test leads at your bench. Any extra test leads or cables borrowed from inventory should be returned after each lab session.

0.2.4 Instructor's Bench and Office Space

Access to the instructor's lab bench and office space is restricted to invitation only.

0.2.5 Use of Tools

Utilize the tools listed on your personal tool list when working in the lab. Refrain from borrowing tools from fellow students. If you require access to program-specific tools, they can be checked out only with proper permission. Note that certain program tools may necessitate safety training before usage. For further details, consult your instructor or lab assistant.

0.2.6 Personal Item Work

Working on personal items such as stereos is not allowed unless you have obtained prior permission from the instructor. If granted permission, such activities should take place outside of lab hours provided you are up to date with your laboratory assignments.

0.2.7 Seating Arrangements

The placement of lab stools and chairs at specific benches serves a purpose; please refrain from relocating them. Should you require specialized seating accommodations, please consult your instructor or lab assistant. If you possess documentation validating your need for specialized seating, arrangements can be made.

0.3 Equipment Rules

0.3.1 Equipment Handling

1. Seek explicit permission from instructors or lab assistants before moving any equipment between bench locations or labs.

2. Handle equipment with care, avoiding any form of abuse. Do not forcefully insert or remove cables or cords. Avoid placing objects on scope probe leads or coaxial cables.

0.3.2 Familiarity with Equipment

1. Take the time to thoroughly read the operator's manuals for the equipment you are using. Before making any adjustments, ensure you have a clear understanding of the purpose and function of each knob or setting. Familiarize yourself with the equipment's operation and intended use.

0.3.3 Dealing with Defective Equipment

1. Before assuming equipment is defective, double-check to rule out operator error.
2. If equipment is found to be defective, tag it with a description of the problem, date, and your signature. Leave the tagged equipment with the instructor. Seek guidance from the instructor or lab assistant if you're unsure how to proceed.
3. If authorized, relocate defective equipment to the designated repair area and obtain a suitable replacement.

0.3.4 Proper Shutdown Procedures

1. Always turn off test equipment at the end of each lab session.
2. Coordinate with fellow users sharing the same power source to ensure all benches are turned off together.

0.3.5 Equipment Accessories and Display Care

1. Do not remove equipment accessories from their assigned drawers.
2. Prevent prolonged display damage by avoiding bright traces on CRT displays. Lower the brightness to the minimum setting if you'll be away from the equipment.

0.3.6 Precise Measurements

1. Set test instruments to the appropriate function and measurement range before taking readings.
2. When dealing with uncertain quantities, start by setting the range switch to its highest available setting.

Conclusion Guidelines

0.4 Conclusion Guidelines

0.4.1 Steps for writing a good Conclusion.

Writing a good lab conclusion is essential for summarizing your experiment, presenting your findings, and demonstrating your understanding of the experiment's purpose and results. Here are some steps to help you write a good lab conclusion:

1. **Restate the Purpose or Objective:** Begin by restating the original purpose or objective of the experiment. Explain what you were trying to investigate or achieve.

2. **Summarize the Experiment:** Provide a brief summary of the experiment's procedures and methods. Highlight the key steps you followed to conduct the experiment.

3. **Present the Data:** Include a concise presentation of the data you collected during the experiment. Use tables, graphs, or charts if necessary to make the data more accessible. Be sure to label your figures appropriately.

4. **Analyze the Results:** Interpret the data you presented in the previous step. Discuss any trends, patterns, or relationships you observed. Explain what the data means in the context of your experiment.

5. **Discuss Errors and Uncertainties:** Acknowledge any potential sources of error or uncertainties in your experiment. Explain how these may have affected your results and conclusions. This demonstrates a critical understanding of the experiment's limitations.

6. **Compare with Hypothesis or Expectations:** If you had a hypothesis or expected outcomes, compare the actual results with your predictions. Discuss whether the data supports or contradicts your initial expectations.

7. **Draw Conclusions:** Based on your data analysis, draw clear and concise conclusions. State what you have learned from the experiment and how it relates to the original purpose or objective.

8. **Relate to Scientific Concepts:** Discuss how your findings relate to relevant scientific concepts, principles, or theories. Show your understanding of the broader scientific context.

9. **Suggest Future Work:** If applicable, suggest potential improvements or further experiments that could build upon your research or address any unanswered questions.
10. **Summarize the Importance:** Summarize the significance of your findings and why they matter. Explain any real-world applications or implications of your results.
11. **Reiterate Key Points:** Reiterate the most important points from your conclusion to reinforce your main messages.
12. **Maintain Conciseness:** Keep your conclusion concise and to the point. Avoid adding new information or data that wasn't discussed in the main body of the report.
13. **Proofread and Edit:** Carefully proofread your conclusion for grammar, spelling, and clarity. Make sure it flows logically and is easy to understand.
14. **Cite Sources:** If you used external sources or references in your report, be sure to properly cite them in your conclusion.

0.4.2 Summary

Remember that a good lab conclusion should effectively communicate the key findings of your experiment, their significance, and your understanding of the scientific principles involved. It should be clear and well-structured, allowing readers to grasp the essence of your work without having to go through the entire report again.

Lab 1

Oscilloscope & Test Equipment Familiarization

1.1 Objective

Welcome to this comprehensive unit that will guide you through mastering the proper use of the oscilloscope and other essential test equipment found on your lab bench. By the conclusion of this unit, you will have acquired the necessary skills and knowledge to confidently operate both the oscilloscope and the function generator. You will also develop a clear understanding of the functions of each control associated with these instruments. Furthermore, you will be adept at generating specific signals using the equipment and accurately performing measurements.

1.2 Reference Documents:

- *Tektronix XYZs of Oscilloscopes* PDF [1]
- *Tektronix TDS Oscilloscope User Manual* PDF [2]
- *Tektronix AFG1022 Arbitrary/Function Generator Quick Start User Manual*PDF [3]
- *Power Supply GPS-4303 User Manual*PDF [4]
- *Tektronix - Get more from your basic oscilloscope with the FFT function* [5]

1.3 Checkoff Sheet:

See Table 1.3 *Oscilloscope & Test Equipment Familiarization Check-Off Sheet* on Page 18.

1.4 Lab Instructions:

1.4.1 Oscilloscope & Function Generator Controls and Specifications

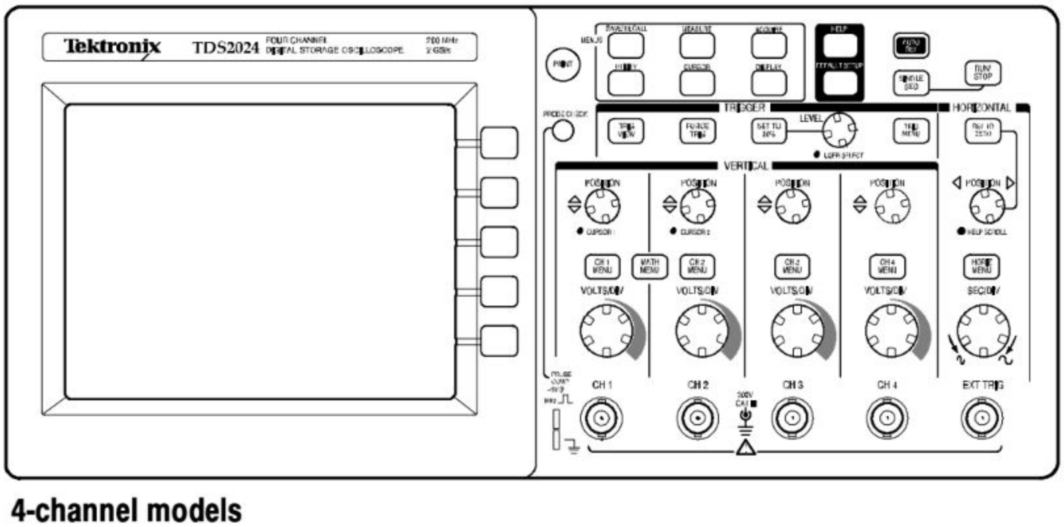


Figure 1.1: TDS2024 Front Panel

1. Familiarize yourself with the oscilloscope's front panel and understand the purpose of each control and button, including any sub-menus or settings accessible through these controls. Refer to *Tektronix TDS Oscilloscope User Manual* PDF [2]

   In your lab book:

   (a) Draw or attach an image of the oscilloscope's front panel refer to Figure 1.1 *TDS2024 Front Panel*.

   (b) List and define each button, control, and sub-menus function.

2. Familiarize yourself with the AFG1022's front panel and understand the purpose of each control and button, including any sub-menus or settings accessible through these controls. Refer to *Tektronix AFG1022 Arbitrary/Function Generator Quick Start User Manual PDF* [3]

   In your lab book:

   (a) Draw or attach an image of the AFG1022's front panel refer to Figure 1.2 *AFG1022 Front Panel*.

   (b) List and define each button, control, and sub-menus function.

3. Familiarize yourself with the oscilloscope's specifications.

   In your lab book:

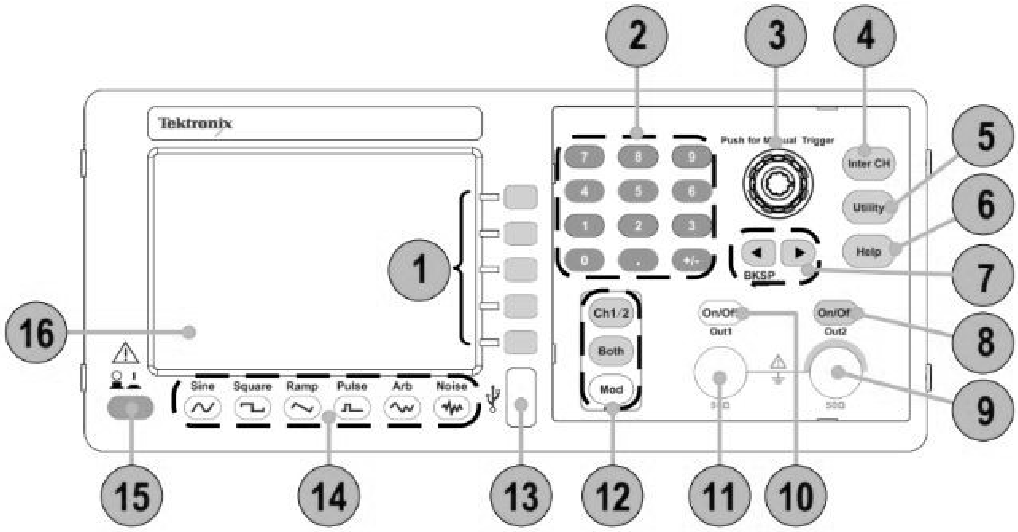


Figure 1.2: AFG1022 Front Panel

(a) Note the bandwidth specification for the TDS2024 oscilloscope.

(b) Provide a clear explanation of what bandwidth means in the context of oscilloscopes. Refer to page 36 of *Tektronix XYZs of Oscilloscopes PDF* [1]

(c) Document the bandwidth specifications of your oscilloscope probes and make sure to record the probe capacitance values for both x1 and x10 settings.

4. Familiarize yourself with the oscilloscope trigger menu and triggering function.

   In your lab book:

   (a) Explain what an untriggered or free-running sweep is and how the oscilloscope achieves triggering. Refer to page 28 of *Tektronix XYZs of Oscilloscopes PDF* [1]

   (b) Document the trigger procedure.

5. Using the Probe Compensation Signal on the oscilloscope, demonstrate to your instructor the difference between an untriggered free-running sweep and a triggered waveform. Be prepared to identify the trigger level, rise/fall settings, and the specific trigger point on the waveform.

   In your lab book:

   (a) Draw or attach an image that shows an untriggered free-running sweep.

   (b) Draw or attach an image that shows a triggered waveform.

1.4.2 Probe Compensation

1. Learn how to properly compensate an oscilloscope probe. Compensate all four of your probes, each probe to its specific channel. Refer to pages 45 and 46 of *Tektronix XYZs*

of Oscilloscopes PDF [1]

In your lab book:

(a) Draw or attach an image that shows an under-compensated probe.

(b) Draw or attach an image that shows an over-compensated probe.

(c) Draw or attach an image that shows a properly compensated probe.

(d) Write a probe compensation procedure.

2. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

1.4.3 Vertical Calibration Verification

1. Verify the calibration of the vertical amplifiers (Volts/Div control). Refer to page 20 of *Tektronix XYZs of Oscilloscopes PDF* [1]

   In your lab book:

   (a) Write a procedure for testing the vertical amplifiers.

   (b) Collect measured data. See Table 1.1 *Vertical Amplifier Calibration Verification* on page 17.

2. Report any equipment issues to the instructor or lab assistant.

1.4.4 Horizontal Calibration Verification

1. Verify the calibration of the horizontal amplifiers (Time/Div control). Refer to page 21 of *Tektronix XYZs of Oscilloscopes PDF* [1]

2. In your lab book:

   (a) Write a procedure for testing the horizontal amplifiers.

   (b) Collect measured data. See Table 1.2 *Horizontal Amplifier Calibration Verification* on page 17.

3. Report any equipment issues to the instructor or lab assistant.

1.4.5 Oscilloscope Measurement Techniques

1. Review Oscilloscope Measurements Techniques. Refer to pages 47 and 48 of *Tektronix XYZs of Oscilloscopes PDF* [1]

2. In your lab book:

   (a) Write a procedure titled "Taking Measurements" and include three subsections titled "Graticule", "Cursors", and "Automatic". Refer to page 34 of *Tektronix TDS Oscilloscope User Manual PDF* [2]

   (b) Document procedures for each of the three methods of measurement.

   Section Check-Off:

3. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

1.4.6 Phase Shift Lissajous Measurements

1. Review Phase Shift Measurements, refer to Refer to page 49 of *Tektronix XYZs of Oscilloscopes PDF* [1]

Tektronix
COMMITTED TO EXCELLENCE

Basic Oscilloscope Measurements: Dual-trace and X-Y Phase

Technique brief

Introduction

At one time or another, you probably watched the marching routines performed by a band during the half-time ceremonies of a football game. Whether you watched the band from the stadium bleachers or from a comfortable chair is unimportant. In either case, you noticed that the relationship of the band's columns changed during these various routines, but that they each maintained a common tempo or number of steps per minute.

Now let's imagine that a band like that one marches the length of a football field. Its columns are physically aligned, and each column is marching at the same tempo. As the band marches, every column passes each 5-yard line at the same time. In other words, the columns are marching "in phase." If, when the band reaches the 50-yard line, all but one of the columns march in place for a moment and then resume marching, one column will be leading the rest of the band. Thus, as the band continues marching down the football field, the leading column will pass each of the remaining 5-yard lines sooner than the rest of the band's columns. That is, the leading column and the rest of the band are now "out of phase."

In electronics, the phrases "in phase" and "out of phase" describe the time relationship between two electrical signals. The measurement of phase differences is important in both electronic design and in troubleshooting electronic equipment. More than likely, you'll use an oscilloscope to measure the phase differences between two electrical signals.

Using an oscilloscope, you can make a phase measurement in two different ways. The method you use depends upon what type of oscilloscope you're using and what you're measuring. The first method of phase measurement, dual-trace, is accomplished more easily than the second. However, you need a dual-channel oscilloscope to make it. The second, X-Y, has more steps, and requires a more careful setup, but can be accomplished on any single channel oscilloscope with an external horizontal (or X) input.

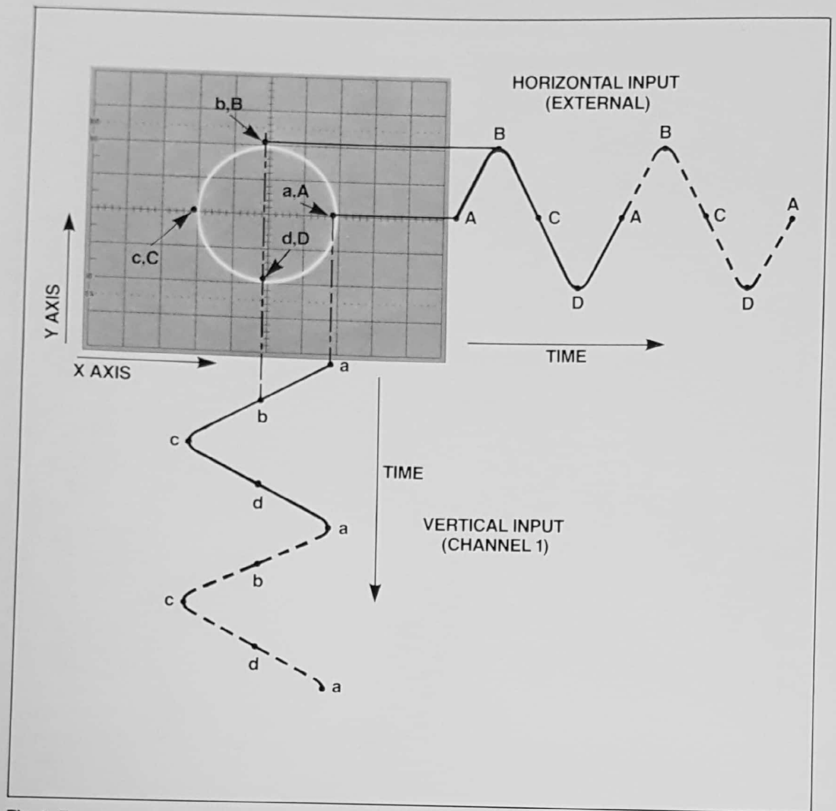
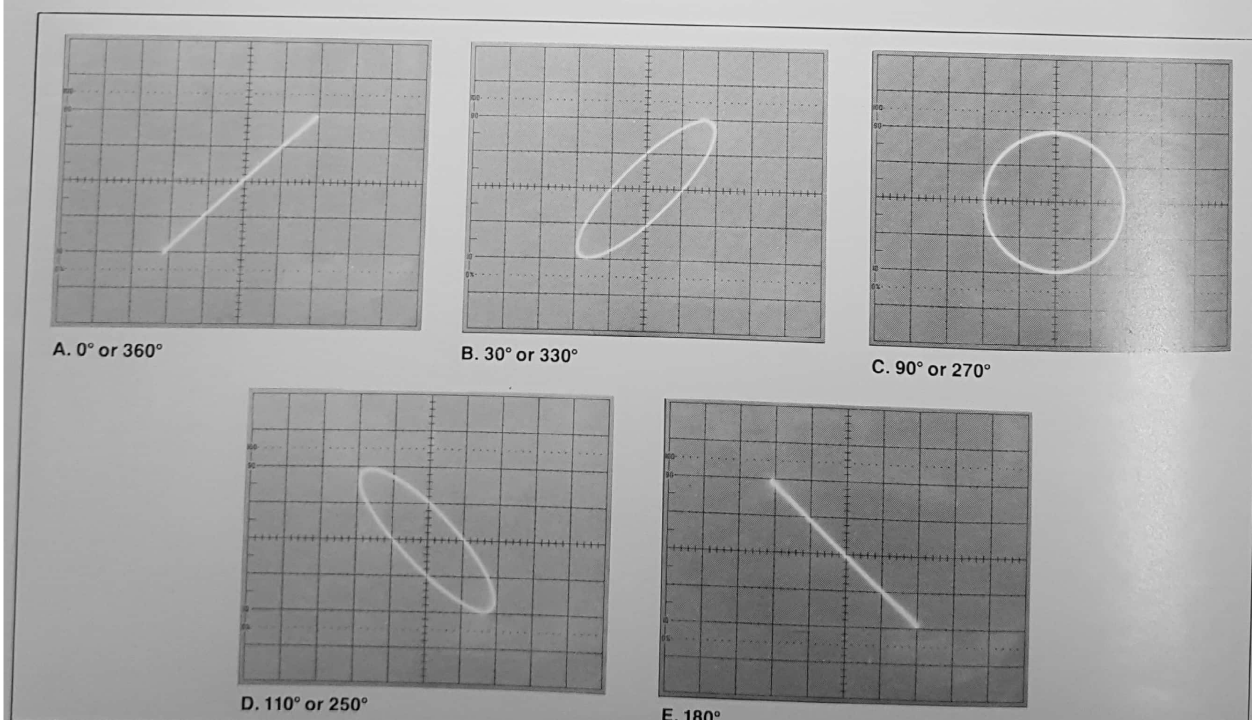


Fig. 1. Formation of a Lissajous figure. (Two sine waves 90° out of phase).

Using the dual-trace method, you'll see two time-shared traces concurrently displayed on the crt screen. Using the X-Y method, you'll see a graph, called a Lissajous (lē′ sə zhoo′) figure, representing the vertical (or Y) input signal as it is plotted against the external horizontal (or X) input signal. The formation of this graph is explained by figure 1.

The shape of a Lissajous figure depends upon the phase difference between the two input signals, the frequency of the two input signals, and the amplitude of the two input signals. Figures 2, 3, and 4 show the effects of phase difference, frequency, and amplitude on a Lissajous figure.

Phase measurements, whether dual-trace or X-Y, are made when the input signals on both the external horizontal (X) and the vertical (Y) input channels are the same frequency. In fact, differences between the two frequencies become readily apparent in both dual-trace and Lissajous displays. In a dual-trace display, if different frequencies are on both channels, then the triggering channel's display will be stable and the other channel's display will be moving. If you measure phase differences using the X-Y method and there are different frequencies on each channel then you'll see the Lissajous figure begin to roll, or its symmetry change.



A. 0° or 360°
B. 30° or 330°
C. 90° or 270°
D. 110° or 250°
E. 180°

Fig. 2. Effect of phase differences on a Lissajous figure.

Now change the vertical mode to DUAL TRACE. Both waveforms should appear on the crt screen. (If necessary adjust the INTENSITY for an easily viewed display.) If the two waveforms are of unequal amplitude, adjust the VOLTS/DIV and VAR controls to obtain signals of equal amplitude. This will not affect the accuracy of your measurement, but will make your analysis of the signal easier. Align the bottom peaks of each waveform with the same horizontal graticule line by using the vertical POSITION controls. Adjust the SEC/DIV (or its VAR control if it has one) to display one waveform period (that is one cycle or 360°) in no more than eight center horizontal graticule divisions. Once you've aligned the reference waveform (in this case channel 1) with the intersection of the center horizontal graticule line and the first vertical graticule line (see figure 5), you're ready to compute the phase difference between the two waveforms.

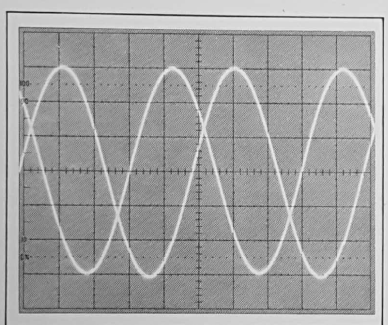


Fig. 5. Align the bottom peaks of each waveform with a horizontal graticule line.

Analyzing Phase Difference

Analyzing phase difference on a dual-trace oscilloscope requires three steps: (1) determining the number of degrees per graticule division, (2) counting the number of divisions between the reference waveform and the second waveform, and (3) computing the phase difference in degrees between the two waveforms.

Notice how many graticule divisions it takes for one complete waveform period to occur. In figure 6, for example, one waveform period occurs in 5.0 graticule divisions. To determine the number of degrees per graticule division, use the following formula.

NUMBER OF DEGREES PER DIVISION
= 360° ÷ Number of Divisions in One Period

Thus, in figure 6,
360° ÷ 5.0 Divisions
= 72° per Division.

When you count the number of horizontal divisions between the two waveforms in figure 6, you should count 1.8. To determine the phase difference between the two waveforms, you'll need to use this formula:

PHASE DIFFERENCE
= Horizontal Difference in Divisions x Degrees per Division

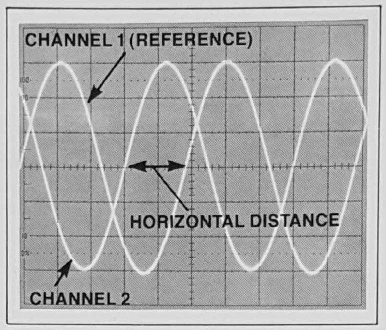


Fig. 6. Determine phase differences—Multiply the number of degrees per division by the number of horizontal divisions between the two waveforms.

Now, using the information you've already derived from figure 6, you can compute the phase difference of the two waveforms.

PHASE DIFFERENCE
= 1.8 Divisions x 72° per Division
= 129.6°

High Resolution Phase Measurements

When the horizontal distance between two waveforms is less than one division, you might find it difficult to make accurate phase measurements. Oscilloscopes equipped with a horizontal magnification (X1-X10) control help make these measurements more accurate. Making high resolution phase measurements is no more difficult than making a regular dual-trace phase measurement. The principle is the same. It just requires a few more steps.

The initial measurement setup is identical, but once you have two waveforms displayed on the crt screen with less than a division between them, you should probably decide to make a high resolution phase measurement. Before doing this, be sure that you compute the number of degrees per division using the method explained above. To make a high resolution phase measurement, set the X1-X10 magnification control to its X10 position. Then rotate the horizontal POSITION control until the display on the crt screen "appears" to be two diagonal lines that cross the center horizontal graticule line. See that at least one of the traces crosses the intersection of a vertical and the center horizontal graticule line, as shown in figure 7.

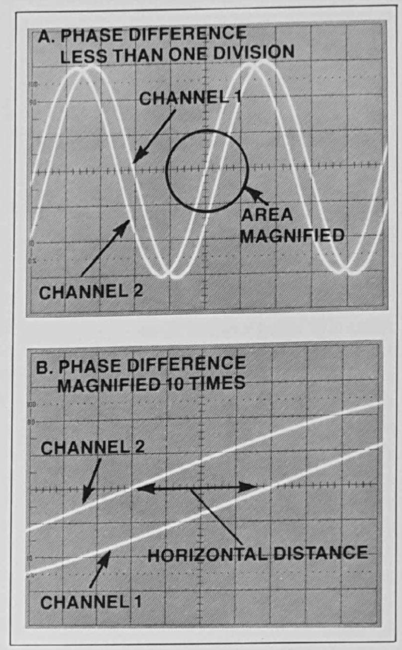


Fig. 7. High resolution phase measurement.

The X10 magnification example merely expands the waveforms without changing their phase relationships. But, whenever you change to a X10 magnified display, the number of degrees per division decreases. In figure 7A, there are 72° per division. When you put the oscilloscope in the X10 magnification mode, there are 7.2° per division (72 ÷ 10 ≐ 7.2° per division). To determine the phase difference between the two waveforms, you still use the formula for phase difference described in the previous section. By substituting these new values into that formula, you can determine the phase difference between the two waveforms in figure 7B.

PHASE DIFFERENCE
= 4 Divisions x 7.2° per Division
= 28.8°

X-Y Phase Measurements

Although you won't see two traces on the crt screen when you make an X-Y phase measurement, what you do see, a Lissajous figure, can help you determine phase relationships.

Setup

On some oscilloscopes, preparing to make X-Y phase measurements takes more steps than on others. If you've just completed the dual-trace phase measurement, then you can use one of the following procedures to quickly make an X-Y phase measurement. The procedure you use will depend upon the type of oscilloscope you're using.

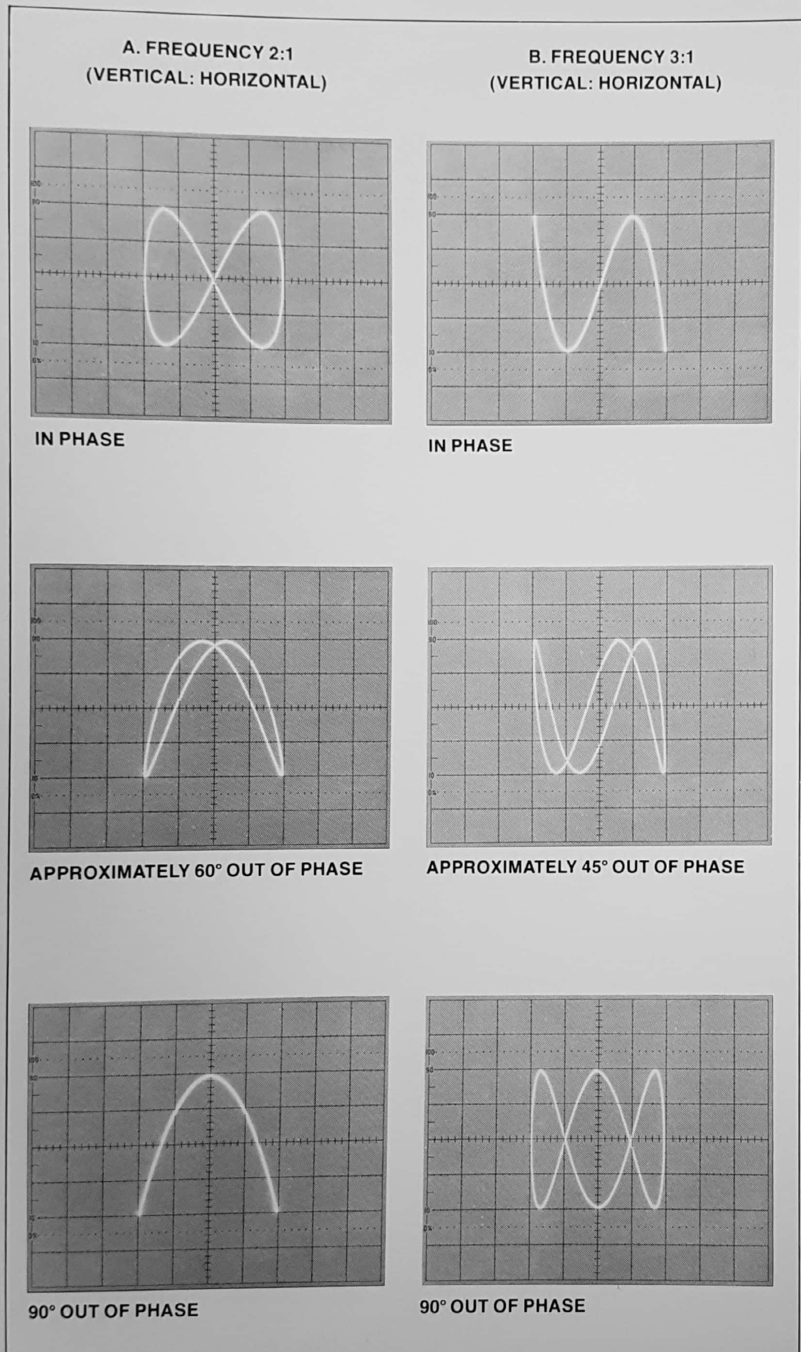


Fig. 3. Effect of frequency on a Lissajous figure at various phase differences.

Even though this technique brief concerns itself with phase measurements, you might be interested in knowing something more about Lissajous figures. Although you can't make a phase measurement with a Lissajous figure when different frequencies exist on the horizontal and vertical input channels, you can find harmonic frequencies. (Harmonic frequencies are integral multiples of a fundamental frequency. For example, a basic frequency of 60 hertz has a second harmonic of 120 hertz, a third harmonic of 180 hertz, and so forth.) Figure 3 illustrates the Lissajous figures which appear when the vertical to horizontal frequency ratio is 2:1 and 3:1. (If the vertical to horizontal ratio is reversed, the figures will rotate 90°.)

Although different frequencies on the horizontal and vertical inputs prohibit you from making phase measurements, different amplitudes do not. You can easily make either type of phase measurement when different amplitudes exist on both channels by making the necessary adjustment (usually the variable control on the VOLTS/DIV control) to compensate for the difference in amplitude.

The following sections contain procedures which give you the ability to setup, make, and analyze phase measurements easily. If you're using a dual-trace oscilloscope, begin with the section that immediately follows; if you're using a single-trace oscilloscope, begin with the section entitled "X-Y Phase Measurements."

Dual-Trace Phase Measurements

Setup

To setup your oscilloscope, verify that it is common grounded with the system to be tested, verify that the system to be tested is grounded, and obtain a free-running trace according to the procedures described in *Basic Oscilloscope Measurements: Setup and Analysis* (AX-3841). The same technique brief describes how to compensate oscilloscope probes. For phase measurements, you'll need to vary that compensation procedure slightly. Connect two identical probes whose cables are of equal lengths to the channel 1 (CH 1) and channel 2 (CH 2) inputs. Select the appropriate vertical mode (CH 1 or CH 2), and follow the procedure described in the above technique brief to compensate both probes. Then set the vertical mode to CH 1.[1]

After you input signals to an oscilloscope, one channel has to be selected as the triggering or reference channel. On some oscilloscopes, this is done for you and you have no control over it, but on more sophisticated dual-trace oscilloscopes you can select either channel as the trigger channel. If your oscilloscope allows you to select the triggering channel, select channel 1. (You could use either channel, but throughout this technique brief let's use channel 1 which is the triggering channel on most oscilloscopes without trigger selection).

If your dual-trace oscilloscope has a CHOP (chopped) or ALT (alternate) switch, set the oscilloscope to either CHOP or ALT. Whether you select a chopped or alternate display depends upon the SEC/DIV control setting. A general rule of thumb is to select the alternate display mode when the SEC/DIV setting is faster than 0.5 ms, and to select a chopped display mode when the setting is slower than 0.5 ms. If your dual-trace oscilloscope doesn't have this control, it probably selects the chopped or alternate display mode for you automatically.

When you're ready to input the signals you want to display, connect the channel 1 probe tip to one test point (the channel 1 probe will provide the triggering or reference waveform on the crt screen), and connect the channel 2 probe tip to a second test point. Then with the vertical mode set to CH 1, perform these steps:

1. Obtain a stable display by using the LEVEL control.
2. Use the vertical POSITION control to approximately center the waveform on the crt screen.
3. Set the VOLTS/DIV and its VAR (variable) control to display a waveform an even number of divisions high.
4. Repeat steps 1, 2, and 3 with the vertical mode set to CH 2.

[1] Either ac or dc coupling may be used. Be aware, however, that using ac coupling at low frequencies will introduce phase shift.

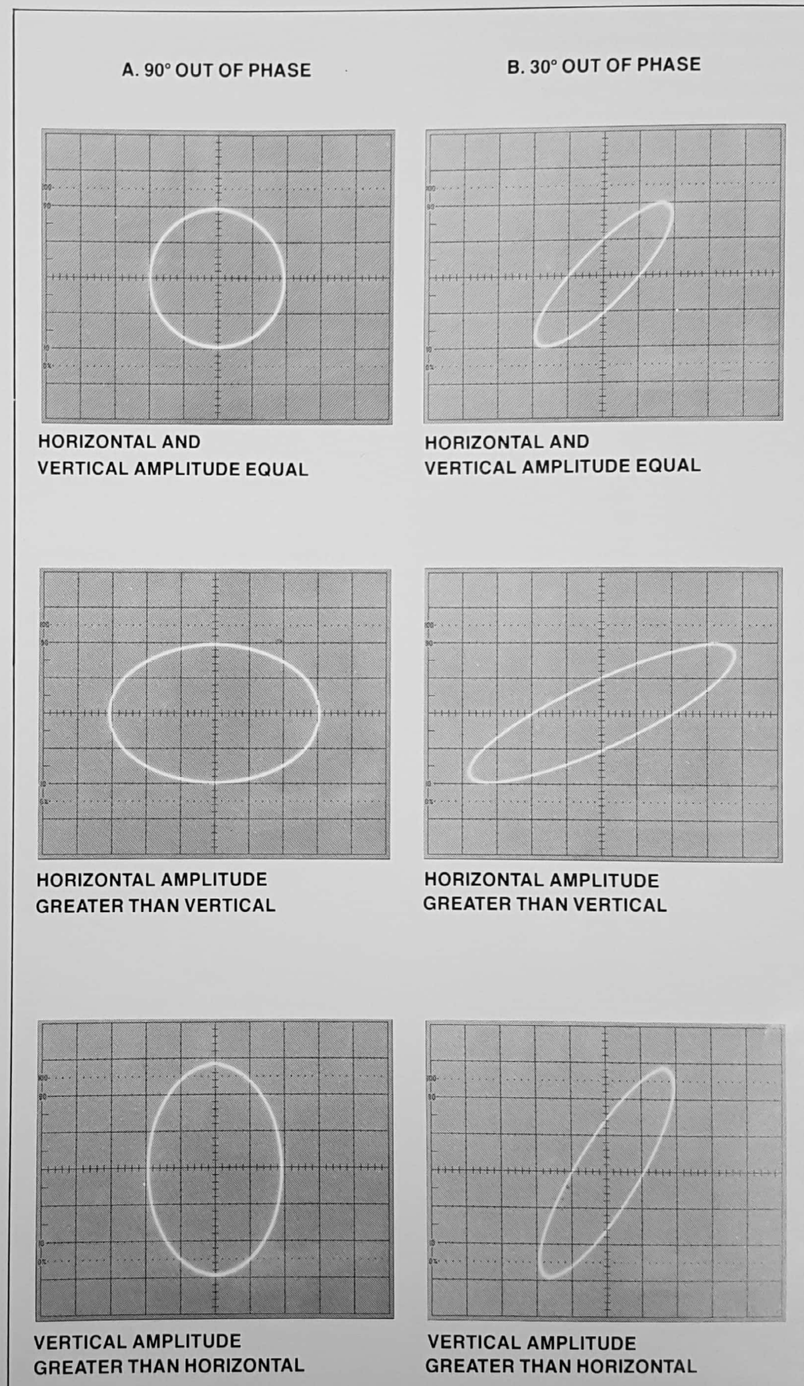


Fig. 4. Effect of amplitude on a Lissajous figure of constant phase.

Procedure 1:
When you use an oscilloscope with an external horizontal input, disconnect the channel 2 probe and connect it to the external input. Select CH 1 as the vertical display mode, switch the oscilloscope into its X-Y mode, and adjust the INTENSITY for an easily viewed display.

Procedure 2:
If your oscilloscope doesn't have an external input, simply set the vertical mode to CH 1 or CH 2, switch the oscilloscope into its X-Y mode and adjust the INTENSITY for an easily viewed display.

When you use a single channel oscilloscope with an external horizontal (X) input, however, you'll need to follow the procedure already described in *Basic Oscilloscope Measurements: Setup and Analysis* (AX-3841) to verify that your oscilloscope is common grounded with the system to be tested, and that the system to be tested and the oscilloscope are both grounded. To compensate two identical probes with equal cable lengths, also follow the above technique brief. After you've compensated both probes, connect one channel 1 (vertical) and the other to the external horizontal input. Once you change the mode of the oscilloscope to X-Y, you should see a Lissajous figure. If you don't, use the BEAM FINDER and the POSITION controls to locate the pattern. After you have a Lissajous figure, adjust the INTENSITY for just enough brightness to view the display easily.[2,3]

By using the POSITION controls, align the Lissajous figure so that one of the edges of its circumference touches the corner formed by a vertical and a horizontal graticule line. (See figure 8.) This adjustment centers the figure and aligns it so that you can easily analyze it.

Analyzing a Lissajous Figure

A Lissajous figure might appear to be difficult to analyze. It's not. Whether you're using a dual-trace or a single-trace oscilloscope, the method is the same: simply count the number of horizontal divisions between the intersections of the Lissajous figure and the center horizontal graticule line (distance A in figure 8), and then count the number of horizontal divisions between the two points on the Lissajous figure with the widest horizontal separation (distance B in figure 8).[4]

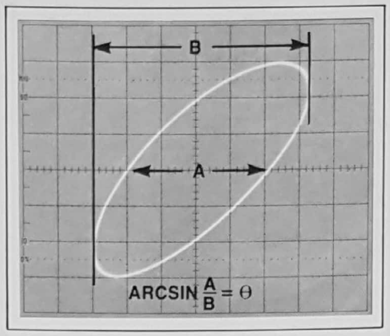


Fig. 8. Determining phase difference using a Lissajous figure.

After determining the distances shown in figure 8, use the arcsine formula below to determine the number of degrees of phase difference between two signals.

$$\text{Arcsin } (A \div B) = \Theta$$

Thus, in figure 8, you can see that the phase difference can be determined by the following substitutions.

$$\text{Arcsin } (4.1 \div 6.3) = \Theta$$
$$\text{Arcsin } 0.6508 = \Theta$$

By consulting a sine table, you can see that the arcsine 0.65082 falls roughly between 40° and 41°. Through interpolation, you'll find that this arcsine corresponds to an angle of about 40.6° (or 40° 36′).

Applications and Summary

Although phase measurements aren't frequently made in basic electronics, don't overlook their usefulness, particularly in audio, and video tape recorder applications.

Whenever you remove and replace the stereo cartridge on the tone arm of your turntable, you have a good chance of replacing it incorrectly. To check your new hookup, you can use an oscilloscope setup for an X-Y phase measurement. This measurement lets you compare the right and left outputs of the audio amplifier in both stereo and monaural modes. If you have hooked up your stereo cartridge incorrectly, you'll see an irregular elipse similar to that in figure 2D when the equipment is set up for stereo operation and a figure like that in figure 2E when the equipment is setup for monaural operation. These figures indicate that the speakers will be operating out of phase. To correct the condition merely reverse one set of the connections going to the + and − pins on the stereo cartridge. Switching these connections should give you an irregular Lissajous figure like the one in figure 2B for stereo operation and the one in figure 2A for monaural operation. These figures indicate that the speakers will be operating in phase.

Electro-mechanical equipment requires periodic service adjustments. One service adjustment required by video tape recorders (vtr's) assures that the magnetic playback heads are in phase. (If the heads aren't aligned, the vtr audio won't sound clear.) The mechanical adjustment that places the playback heads in phase is aided by the use of an oscilloscope. By setting up the oscilloscope for an X-Y phase measurement and connecting the probes and their grounds to the connections of the playback heads designated by the vtr's service manual, you can quickly tell if the heads are operating in phase. If they are you'll see a Lissajous figure like that in figure 2A. If the heads are out of phase, then you'll see an ellipse similar to that in figure 2B, and you'll have to make the necessary mechanical adjustment to place the playback heads back in phase.

This technique brief explained how to make phase measurements using the dual-trace or X-Y measurement methods, and introduced you to the use of Lissajous figures. It is a part of a growing program dedicated to educating potential users about the capabilities and applications of TEKTRONIX Instrumentation. To obtain the other technique briefs and application notes in this program, or for information about TEKTRONIX Products, contact your Tektronix Field Engineer, Distributor, or Representative.

[2] Either ac or dc coupling may be used. Be aware, however, that ac coupling introduces phase differences at low frequencies.

[3] X-Y phase measurements are limited to low frequencies due to the electrical differences between the vertical and horizontal amplifier at an oscilloscope.

[4] If you want, you can use the vertical distances which correspond to distances A and B in figure 8, but remember not to mix the horizontal and vertical distances in the same measurement.

References:

1. Rider, John F. 1970. *Obtaining and Interpreting Test Oscilloscope Traces*. New York: John F. Rider Publishing, Inc.
2. Lenk, John D. 1971. *Handbook of Electronic Test Equipment*. Englewood Cliffs, N.J.: Prentice-Hall, Inc.
3. Lenk, John D. 1968. *Handbook of Oscilloscopes: Theory and Application*. Englewood Cliffs, N.J.: Prentice-Hall, Inc.

2. In your lab book:

   (a) Write a procedure titled "Phase Shift Measurements" that details what a Lissajous pattern is and how to set up the oscilloscope to perform XY Lissajous measurements. Refer to page 100 of *Tektronix TDS Oscilloscope User Manual PDF* [2]

   (b) Draw or attach Figure 1.3 *Phase Shift Lissajous Measurements.*

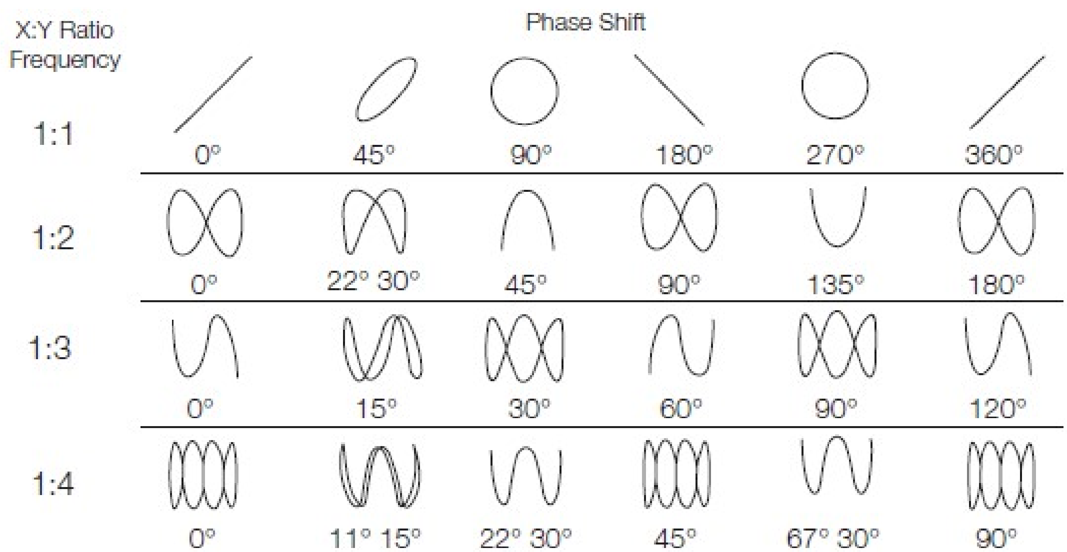


Figure 1.3: Phase Shift Lissajous Measurements

   (c) Use the AFG1022 and the TDS2024 to produce and capture a measured version of Figure 1.3 *Phase Shift Lissajous Measurements.*

   Section Check-Off:

3. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

1.4.7 Fast Fourier Transform

1. Fast Fourier Transform, review *Tektronix - Get more from your basic oscilloscope with the FFT function article* [5]

2. Review FFT Measurements, refer to page 61 of the *Tektronix TDS Oscilloscope User Manual PDF* [2]

3. Throughout the semester, we will use FFT to measure and calibrate RC Circuit Roll-Off in dB, Voutp Max of amplifiers, and Cross-Over distortion in Push-Pull amplifiers.

4. In your lab book:

   (a) Describe what the FFT measurement is and what it is used for.

   (b) Set your function generator to a 10vpp 1Khz square wave. Use CH1 of your oscilloscope to measure and verify the square wave. Press the math button and select type FFT. Adjust the horizontal control to 1.25KHz and position the wave to be similar to Figure 1.4 *FFT Measurements*. Press the cursor button and select type Frequency. Set cursor 1 to the 1Khz position

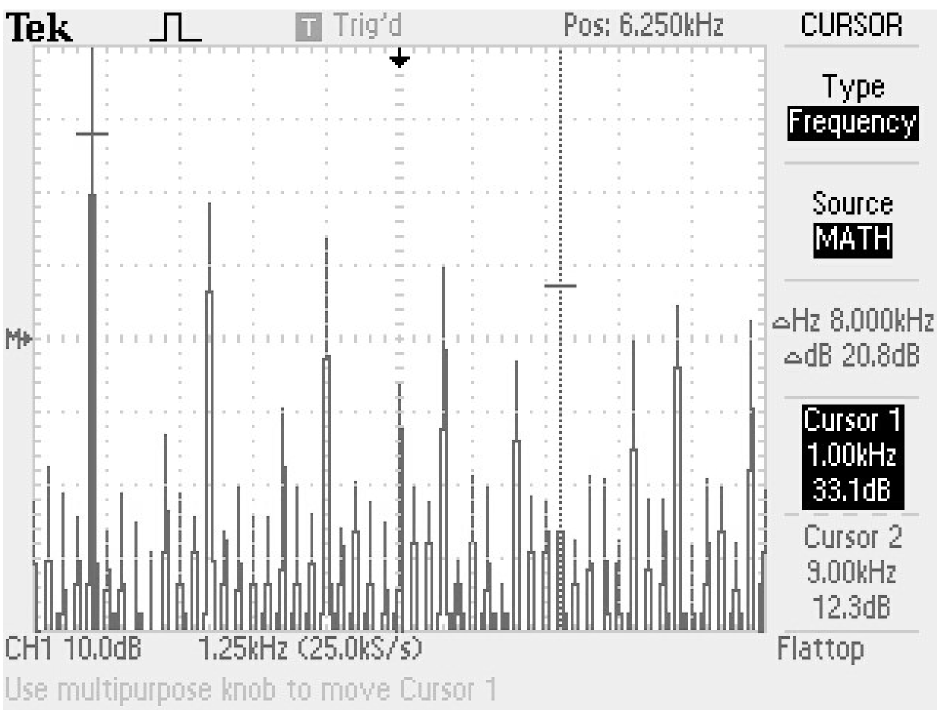


Figure 1.4: FFT Measurements

   (c) Place cursor one on the Fundamental frequency (1Khz). Draw or attach an image of your FFT measurement. Use cursor 2 to document the frequency and dB loss of each harmonic frequency.

   (d) Change the Function Generator from square wave to sine wave and document findings.

(e) Change the Function Generator from square wave to ramp wave and document findings.

5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

1.5 Collected Data

- See *Table Formatting and Data Sets* on page 16.
- Include all data sets referenced in the lab.

1.6 Key Terms

Define The Following:

- Attenuation
- Averaging
- Bandwidth
- Circuit Loading
- Compensation
- Coupling
- Division
- Frequency Response
- Gain Accuracy
- Graticule
- Horizontal Sweep
- Loading
- Noise
- Oscilloscope
- Period
- Phase Shift
- Pulse Width
- Rise Time
- Signal Source
- Slope
- Time Base
- Trigger
- XY Mode

1.7 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

1.8 Table Formatting and Data Sets

Table 1.1: Vertical Amplifier Calibration Verification (Section 1.4.3).

Volts/Div Control	DC Supply Settings	Measured Voltage
200mV/Div	1VDC	
500mV/Div	1VDC	
1V/Div	1VDC	
2V/Div	10VDC	
5V/Div	10VDC	
10V/Div	10VDC	
10V/Div	50VDC	
20V/Div	50VDC	
50V/Div	50VDC	

Table 1.2: Horizontal Amplifier Calibration Verification (Section 1.4.4).

Time/Div Control	Function Generator	Measured Frequency
50mS/Div	2.5HZ	
5mS/Div	25HZ	
500uS/Div	250HZ	
50uS/Div	2.5KHZ	
5uS/Div	25KHZ	
500nS/Div	250KHZ	
50nS/Div	2.5MHZ	
5nS/Div	25MHZ	

Table 1.3: Oscilloscope & Test Equipment Familiarization Check-Off Sheet

<table>
<tr><td colspan="4" align="center">RCET 2252
Clinical Assistant Professor
Timothy Leishman
Oscilloscope & Test Equipment
Check-Off Sheet</td></tr>
<tr><td colspan="2">Name:</td><td colspan="2">Lab Start Date:</td></tr>
<tr><td>Check-Off</td><td>Section</td><td>Date</td><td>Instructor Int.</td></tr>
<tr><td>Probe Compensation</td><td>1.4.2</td><td></td><td></td></tr>
<tr><td>Vertical Calibration</td><td>1.4.3</td><td></td><td></td></tr>
<tr><td>Horizontal Calibration</td><td>1.4.4</td><td></td><td></td></tr>
<tr><td>Oscilloscope Measurement Techniques</td><td>1.4.5</td><td></td><td></td></tr>
<tr><td>Phase Shift Lissajous Measurements</td><td>1.4.6</td><td></td><td></td></tr>
<tr><td>Fast Fourier Transform</td><td>1.4.7</td><td></td><td></td></tr>
<tr><td colspan="4" align="center">Instructor Notes:</td></tr>
<tr><td colspan="4"></td></tr>
</table>

Lab 2

RC Circuits

2.1 Objective

Welcome to this advanced laboratory experiment, where you will embark on an in-depth exploration of series RC circuits, Integration, Differentiation, and Switching Diodes, with a primary focus on pulse theory. This lab has been crafted to enhance your comprehension of pulse circuit theory and its practical application. Throughout this experiment, you will not only gain mastery over the fundamental principles governing series RC circuits and pulse theory but also cultivate the essential skills required for the precise construction, analysis, and graphing of instantaneous voltage waveforms. Moreover, you will undertake the challenge of verifying pulse theory formulas introduced in RCET's third semester, further reinforcing your understanding of advanced concepts. By the conclusion of this hands-on experience, you will acquire a robust foundation in RC circuit analysis and the practical application of pulse theory.

2.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- *Solid State Pulse Circuits* Chapters 1 & 2 [6]

2.3 Checkoff Sheet:

See Table 2.7 *RC Circuits Check-Off Sheet* on Page 32.

2.4 Lab Instructions:

2.4.1 Frequency Response with Rise Time and Tilt

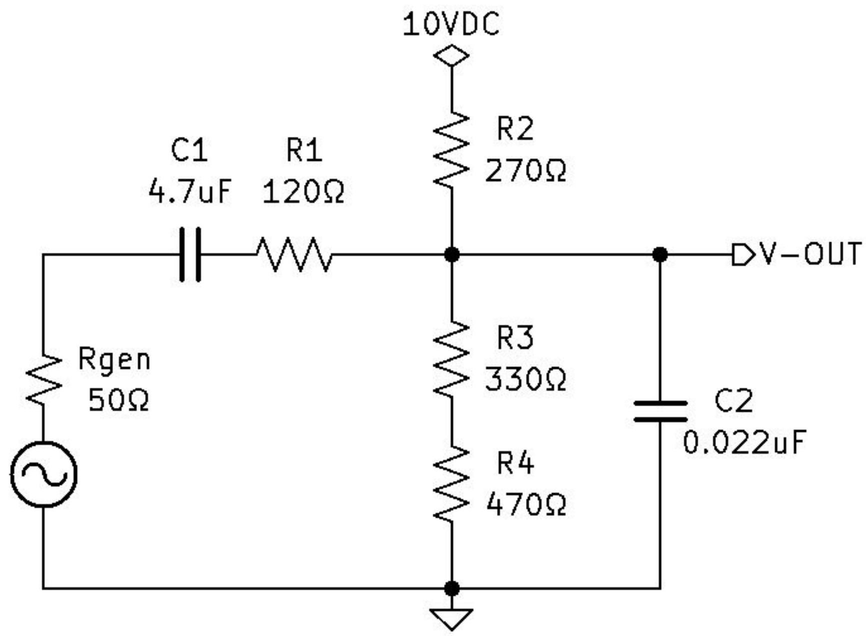


Figure 2.1: RC Circuit 1 (from First Semester)

1. See Figure 2.1 *RC Circuit 1 (from First Semester)*. Refer to your first-semester lab book.

   In your Lab book:

   (a) Draw or attach the schematic *RC Circuit 1 (from First Semester)* Figure 2.1

   (b) Calculate all DC values.

   (c) Calculate Vout at mid-band

   (d) Calculate FC_{LOW} and FC_{HIGH}.

   (e) Draw the predicted Bode Plot for the circuit.

   (f) Build and measure the circuit.

   (g) Document the measured waveforms of V_{GEN} and V_{OUT} at mid-band, FC_{LOW} & FC_{HIGH}.

2. F_{CH} Pulse Theory Measurement:

   (a) Discuss High-Frequency Distortion and its causes.

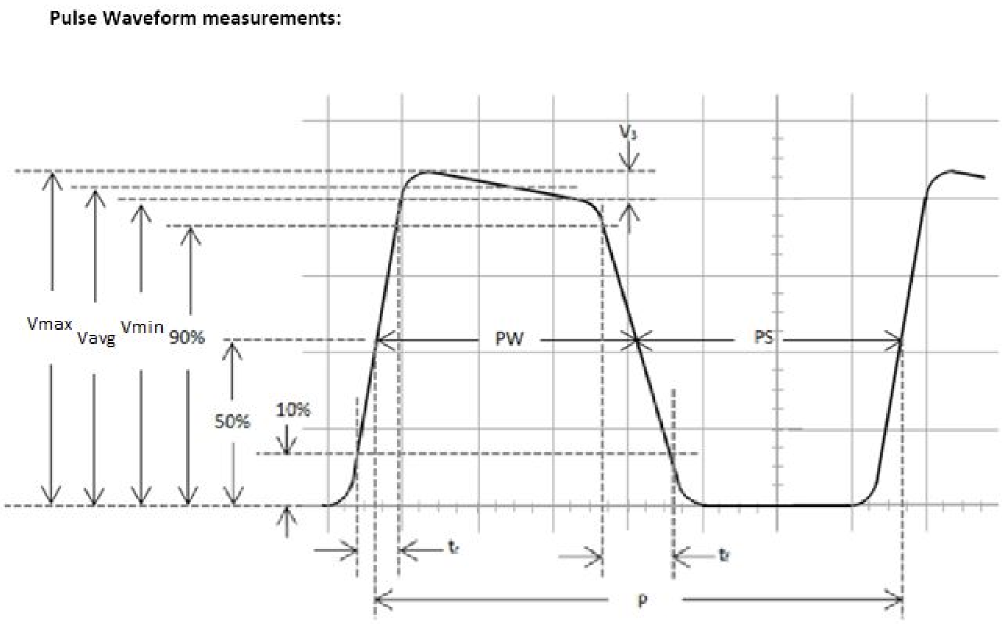


Figure 2.2: Pulse Waveform Measurements

(b) Draw or attach Figure 2.2 *Pulse Waveforms Measurements.*

(c) Change the function generator from a sine-wave to a square-wave at 3vpp for Figure 2.1 *RC Circuit 1 (from First Semester).*

(d) Adjust the frequency so the waveform tilt is minimized, $\approx 10K_{HZ}$.

(e) Select Volts/Div Fine and adjust so that the waveform voltage peaks are exactly 5 divisions.

(f) Center the waveform vertically. See Figure 2.3 *Rise Time Oscilloscope setup 1.*

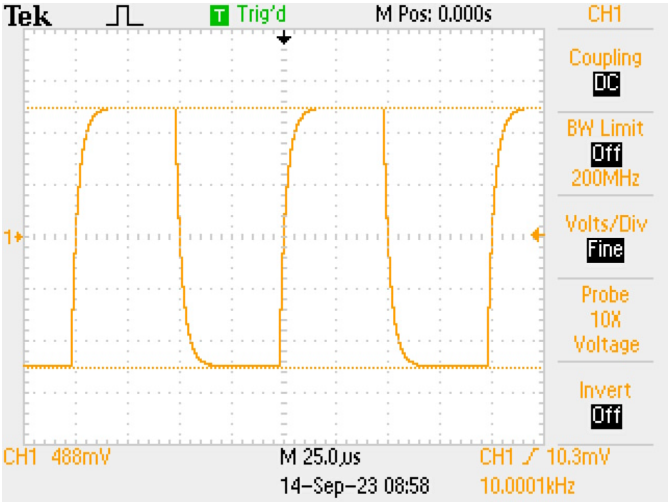


Figure 2.3: Rise Time Oscilloscope setup 1

(g) Adjust the Time/Div to take the rise time measurement with the cursors. Place the cursors at the 10% and 90% crossings (2Div from the top and bottom). Refer to Figure 2.4 *Rise Time Measurement*.

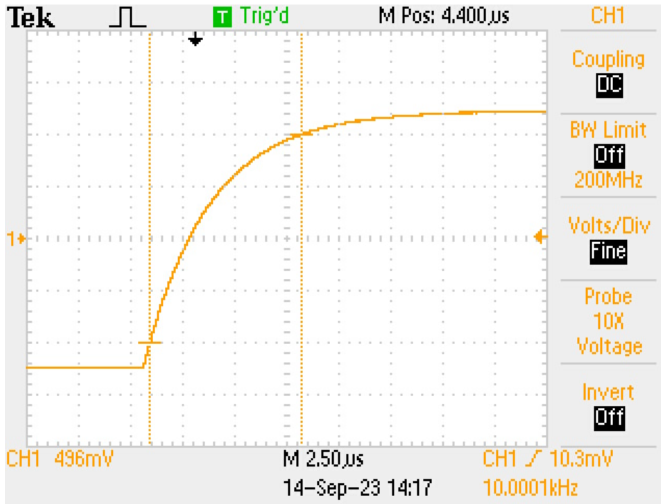


Figure 2.4: Rise Time Measurement

(h) Calculate F_{CH} using the measured rise time.

$$F_{CH} = \frac{0.35}{t_r}$$

(i) Compare the results to the previously measured F_{CH} from step 1.

3. F_{CL} Pulse Theory Measurement:

(a) Discuss Low-Frequency Distortion and its causes.

(b) Assemble circuit Figure 2.1 *RC Circuit 1 (from First Semester)* and set the function generator to 3vpp square-wave.

(c) Adjust the frequency so the waveform tilt is prominent, $\approx 500_{HZ}$. See Figure 2.5 *Tilt Setup*.

(d) Adjust the horizontal and vertical controls to accurately measure the tilt. See Figure 2.6 *Tilt Measurement*.

(e) Measure the Tilt:

$$Tilt = \frac{V_{MAX} - V_{MIN}}{APA}$$

(f) Calculate F_{CL}:

$$F_{CL} = \frac{Tilt}{2\pi PW}$$

(g) Compare the results to the previously measured F_{CL} from step 1.

(h) Collect measured data. See Table 2.9 *RC Circuit 1 (from First Semester)* (Section 2.4.1). on page 29.

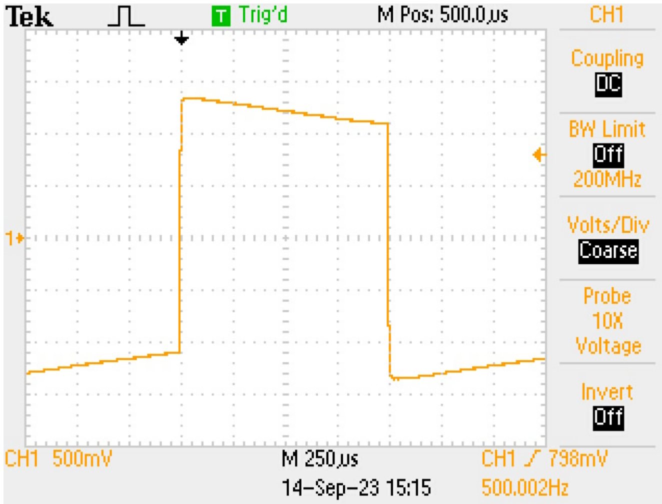


Figure 2.5: Tilt Setup

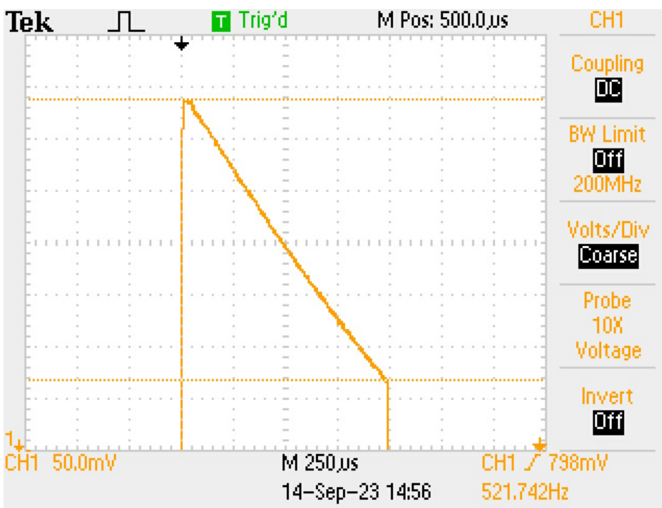


Figure 2.6: Tilt Measurement

4. Double the capacitance value of C1:
   (a) Predict the new F_{CL}.
   (b) Measure the new F_{CL} and explain any discrepancies between the predicted and measured values.
5. With C2 removed from the circuit:
   (a) Predict the new F_{CH}.
   (b) Measure the new F_{CH} and explain any discrepancies between the predicted and measured values.

6. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

2.4.2 Capacitor Charge Formula and Tau Review

1. In your Lab book:
   (a) Write and Define the Capacitor Charge Formula.
   (b) Define τ for an RC circuit
   (c) Show the percent of charge at 1τ, 2τ, 3τ, 4τ, and 5τ.

2.4.3 Cycles to Stabilization, V_{MAX}, V_{MIN}, & AWV Formulas.

1. In your Lab book:
   (a) Write and define the Cycles to Stabilization formula.
   (b) Write and define the V_{MAX} formula.
   (c) Write and define the V_{MIN} formula.
   (d) Write and define the AWV formula.

2.4.4 Verification of the Cycles to Stabilization, V_{MAX}, & V_{MIN} Formulas.

In your Lab book:

1. Design an RC circuit with the following parameters:
   (a) Vgen = $1K_{HZ}$, Square-Wave, 0v to 10V, 50%DC.
   (b) R=1KΩ & C=1uF
2. Calculate the following:
   (a) Cycles to Stabilization
   (b) V_{MAX} & V_{MIN}
   (c) AWV
3. Using the Capacitor Charge Formula, calculate 10 cycles of capacitor and resistor voltage in reference to Vgen.

(a) Draw and appropriately label the schematic

(b) Show all calculations and predicted waveforms

(c) Compare Capacitor Charge Formula calculations to the previous Cycles to Stabilization, V_{MAX} & V_{MIN} calculations.

4. Build, measure, and analyze the circuit.

   (a) Document the measured waveforms.

   (b) Compare and analyze the calculated and measured results.

   (c) Answer this question: Does the data collected for this experiment verify the accuracy of the Cycles to Stabilization, V_{MAX}, V_{MIN}, & AWV formulas?

5. Collect calculated and measured data. See Table 2.2 *Cycles To Stabilization* on page 29.

6. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

2.4.5 RC Integration

1. Define RC Integration, include the following:

   (a) Definition of Integration.

   (b) RC Integration Schematic.

   (c) τ in terms of time (PW).

   (d) Time (PW) in terms of τ.

2. Design an RC Integration circuit using the following parameters:

   (a) $V_{GEN} = 0$ to $10v_p$ square-wave

   (b) Frequency $= 5K_{HZ}$ & R $= 1K\Omega$

   (c) Draw and appropriately label the schematic.

   (d) Calculate:

   - C
   - Cycles to Stabilization
   - V_{MAX}
   - V_{MIN}
   - AWV

(e) Draw the stabilized calculated capacitor and resistor voltage waveforms in reference to the generator.

3. Build, measure, and analyze the circuit.
   (a) Document the measured waveforms.
   (b) Compare and analyze the calculated and measured results.
4. Collect calculated and measured data. See Table 2.3 *RC Integration* on page 30.
5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

2.4.6 RC Differentiation

1. Define RC Differentiation, include the following:
   (a) Definition of Differentiation.
   (b) RC Differentiation Schematic.
   (c) τ in terms of time (PW).
   (d) Time (PW) in terms of τ.
2. Design an RC Differentiated circuit using the following parameters:
   (a) $V_{GEN} = 0$ to $10v_p$ square-wave
   (b) C = $1\mu F$ & R = $1K\Omega$
   (c) Draw and appropriately label the schematic.
   (d) Calculate:
      i. PW and Frequency
      ii. Cycles to Stabilization
      iii. V_{MAX}
      iv. V_{MIN}
      v. VR at 1τ, 2τ, 3τ, 4τ, & 5τ
      vi. VC at 1τ, 2τ, 3τ, 4τ, & 5τ
   (e) Draw the stabilized calculated capacitor and resistor voltage waveforms in reference to the generator, including voltages and timing at 1τ, 2τ, 3τ, 4τ, & 5τ.
3. Build, measure, and analyze the circuit.
   (a) Document the measured waveforms.

(b) Compare and analyze the calculated and measured results.

4. Collect calculated and measured data. See Table 2.4 *RC Differentiation* on page 30.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

2.4.7 RC Circuits Sine-wave Instantaneous Voltages

1. Design an RC sine-wave circuit using the following parameters:

   (a) $V_{GEN} = 10v_p$ sine-wave.

   (b) C = 1μ F & R = $1K\Omega$.

   (c) Draw and appropriately label the schematic.

   (d) Calculate the following:

      i. Critical frequency F_C.

      ii. Total circuit impedance Z_T with phase angle.

      iii. V_C & V_R with phase angles.

   (e) Use the V_{INST} formula to calculate 10 data points of the cycle waveform, 0%, 10%, 20%,..., 100%. Do this for V_{GEN}, V_R, and V_C

   (f) Accurately plot the calculated waveforms.

2. Build, measure, and analyze the circuit.

   (a) Document the measured waveforms.

   (b) Compare and analyze the calculated and measured results.

3. Collect calculated and measured data. See Table 2.5 *RC Circuits Sine-wave Instantaneous Voltage Part 1* on page 30 and Table 2.6 *RC Circuits Sine-wave Instantaneous Voltage Part 2* on page 31.

4. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

2.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 29.
- Include all the data sets referenced in the lab.

2.6 Key Terms

Define The Following:

(a) Draw or attach Figure 2.4.1 Pulse Waveforms Measurements

(b) Period, PW, PS, PRF, Duty Cycle, APA, Tilt, Rise Time, and Fall Time.

(c) Formulas to calculate AWV, FCH, and FCL.

(d) Capacitor Charge Formula and capacitor charge at 1τ, 2τ, 3τ, 4τ, & 5τ.

(e) Cycles to Stabilization, V_{MAX} & V_{MIN} formulas.

(f) Characteristics of an RC Integration Circuit.

(g) Characteristics of an RC Differentiation Circuit.

(h) RC Sine-wave Instantaneous Voltage Formula.

2.7 Key Formulas

- List and define each of the key formulas used in this lab.

2.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

2.9 Table Formatting and Data Sets

Table 2.1: RC Circuit 1 (from First Semester). (Section 2.4.1).

Section.2.4.1	V_{DC}	V_{R1}	V_{R2}	V_{R3}	V_{R4}	V_{OUT}
Calculated DC						
Measured DC						
Section.2.4.1	V_{GENpp}	V_{OUTpp}	$VR1_{pp}$	$VR2_{pp}$	$VR3_{pp}$	$VR4_{pp}$
Calculated AC						
Measured AC						
Section.2.4.1	FC_LSine	FC_HSine	$Tilt$	$Time_{Rise}$	$FC_LSqr.$	$FC_HSqr.$
Calculated FC						
Measured FC						

Table 2.2: Cycles to Stabilization (Section 2.4.4).

Section.2.4.4	$Cycles$	V_{MAX}	V_{MIN}	AWV
Calculated				
Measured				

Table 2.3: RC Integration (Section 2.4.5).

Section.2.4.5	C	$Cycles$	V_{MAX}	V_{MIN}	AWV
Calculated					
Measured					

Table 2.4: RC Differentiation (Section 2.4.6).

Section.2.4.6	PW	$Freq$	$Cycles$	V_{MAX}	V_{MIN}
Calculated					
Measured					
Section.2.4.6	$VR_{1\tau}$	$VR_{2\tau}$	$VR_{3\tau}$	$VR_{4\tau}$	$VR_{5\tau}$
Calculated					
Measured					
Section.2.4.6	$VC_{1\tau}$	$VC_{2\tau}$	$VC_{3\tau}$	$VC_{4\tau}$	$VC_{5\tau}$
Calculated					
Measured					

Table 2.5: RC Circuits Sine-wave Instantaneous Voltages Part 1 (Section 2.4.7).

Section.2.4.7	V_{GEN}	C	R	F_C	$V_C\ \angle^\circ$	$V_R\ \angle^\circ$
Calculated	$10V_P$	$1\mu F$	$1K\Omega$			
Measured						

Table 2.6: RC Circuits Sine-wave Instantaneous Voltages Part 2 (Section 2.4.7).

Section.2.4.7	$Time$	V_{GEN} $Calc.$	V_{GEN} $Meas.$	V_R $Calc.$	V_R $Meas.$	V_C $Calc.$	V_C $Meas.$
$Reference$	$0mS$	$0V$	$0V$				
10% cycle							
20% cycle							
30% cycle							
40% cycle							
50% cycle		$0V$	$0V$				
60% cycle							
70% cycle							
80% cycle							
90% cycle							
100% cycle							

Table 2.7: RC Circuits Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

RC Circuits

Check-Off Sheet

Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
RC Circuit 1 (from First Semester)	2.4.1		
Verification Cycles to Stabilization	2.4.4		
RC Integration	2.4.5		
RC Differentiation	2.4.6		
RC Circuits Sine-wave Inst. Voltages	2.4.7		

Instructor Notes:

Lab 3

Multi-Stage Amplifier: Design, Analysis, and Low Critical Frequency

3.1 Objectives

Objective A: Design and Analysis of a PNP Multi-Stage Amplifier to include calculations and measurements of DC Voltages and Currents, Biasing Optimization, Amplifier Gains, Component Powers, and Lower Critical Frequencies.

1. **Calculate DC Voltages and Currents**: Students should be able to determine the direct current (DC) voltages and currents at various points in an electronic circuit. This involves applying principles of Ohm's Law, Kirchhoff's law, and Thevenin's Theorem.

2. **Biasing Current Paths**: Understand how to set up biasing circuits to establish the desired operating point for PNP transistors.

3. **Signal Current Paths**: Identify and analyze the paths that carry AC (signal) currents through the circuit, considering components like coupling capacitors and bypass capacitors.

4. **Amplifier Gains**: Calculate the voltage, current, and power gain of an amplifier, typically measured in decibels (dB) or as a unit-less ratio.

5. **Amplifier Frequency Response**: Analyze how the gain of an amplifier varies with frequency. This includes determining the upper and lower critical frequencies (the frequencies at which the gain starts to roll off significantly) and creating a Bode plot to visualize the frequency response.

Objective B: Demonstrate the Proper Use of the Oscilloscope, DMM (Digital Multimeter), and Sweep Audio Generator to Obtain Accurate Measurements.

1. **Oscilloscope**: Learn how to properly set up and use an oscilloscope to visualize voltage waveforms, measure voltage levels, and observe signal characteristics like frequency and phase.

2. **DMM (Digital Multimeter)**: Understand how to use a DMM to measure voltage, current, resistance, and other electrical parameters accurately. This includes selecting the appropriate measurement range and function on the DMM.

3. **Sweep Audio Generator**: Demonstrate how to use a sweep audio generator to generate a range of audio frequencies for testing and analysis, including measuring the response of circuits at different frequencies.

To achieve these objectives, students may need to work with various electronic components and circuits, perform calculations, and use measurement instruments like oscilloscopes, DMMs, and sweep audio generators. Circuit calculations and predictions with hands-on experimentation be essential for gaining practical skills in electronics and circuit analysis.

The successful completion of this lab should equip students with the knowledge and skills required to design and analyze multi-stage amplifiers, make accurate measurements, and understand the behavior of amplifiers across different frequencies.

3.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- *Tektronix AFG1022 User Manual* [3]
- *Multi-Stage Schematic PDF* [7]
- *Multi-Stage PCB Layout PDF* [8]

3.3 Checkoff Sheet:

See Table 3.4 *Multi-Stage Amplifier Part 1 Check-Off Sheet* on Page 41.

3.4 Amplifier Design Parameters

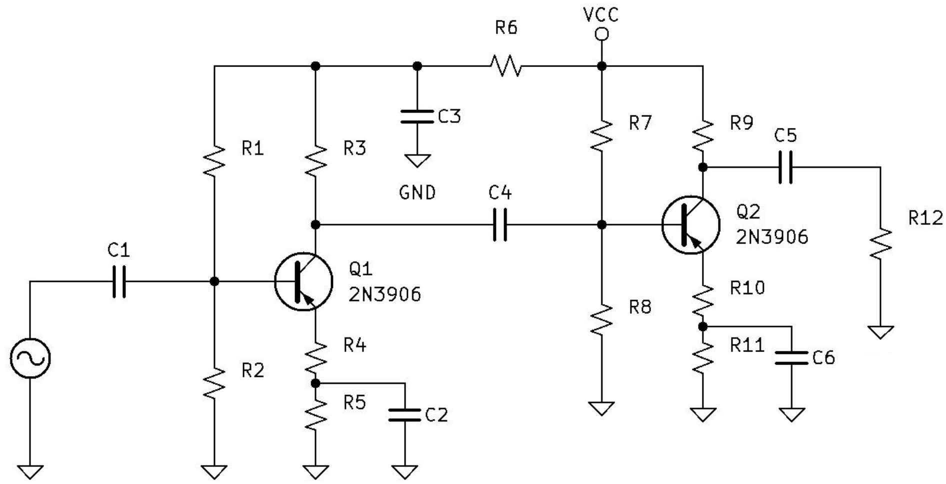


Figure 3.1: Two Stage Amplifier Design

Design Parameters:

- $VCC = -25V$
- P_{Q1} & $P_{Q2} = 312.5mW$
- Optimized Biasing
- Q_1 *and* Q_2, $\Delta V = -10$
- $\beta = 200, for\; Q_1\; and\; Q_2,$
- $I_{R2} = 10 \times IB_{Q1}$
- $I_{R8} = 10 \times IB_{Q2}$
- $R12 = 10 \times R9$
- $R3 = \frac{RL\_Equivalent_{Q1}}{10}$

3.4.1 Multi-Stage Circuit Design

1. Draw or attach the *Multi-Stage Schematic*[7] in your lab book.
2. Create a DC redraw for both Q_1 and Q_2.
3. Show all DC calculations including Power calculations.
4. Create an AC circuit redraw schematic.
5. Show all AC mid-band gain calculations.
6. Create a DC/AC load line and show calculations for $Vout_{MAXP}$ and Vin_{MAXP}.

3.4.2 Resistor Standard Values and Circuit Analysis

1. Carefully round each calculated resistor value to a standard value.

2. Create a table to include circuit designed values VS. standard resistor values to include voltages and powers. Also include space for measured data.

3. Analyze the circuit with the standard resistor values:

   - For Q2 provide detailed procedure examples for both Thevenin Analysis and Kirchhoff Analysis.
   - For Q1 provide only Kirchhoff Analysis.

4. Develop accurate DC & AC Load lines for Q2. Calculate $Vout_{MAXp}$ and Vin_{MAXp}.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

3.4.3 Circuit Measurements

1. Measure all DC voltage values and verify that the measurements align with the calculated values.

2. Prior to making AC measurements, document a procedure for verifying mid-band frequency operation (verify that the output signal of a two stage common emitter amplifier is in-phase with the input).

3. At mid-band frequency, measure voltage gain, the maximum peak output voltage, and the minimum peak input voltage.

4. Provide a detailed procedure on how to calibrate the circuit to precisely adjust the voltage gain of each circuit.

5. Provide a detailed procedure on how to verify and adjust (if needed) the optimization of Vout Max Peak $Vout_{MAXp}$.

6. Collect measured data.

7. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

3.4.4 Low Frequency Response Calculations

1. List the steps for calculating FC_{Low}.
2. Find the Thevenin Resistance for each capacitor.
3. Calculate each capacitor value to provide an FC_{Low} of 1KHz.
4. Round each capacitor value up to the next standard value and recalculate it's critical frequency.
5. Calculate FC_{LOW} using standard value capacitors.
6. Create a table for the calculated Thevenin Resistances and Critical Frequencies for the capacitors and calculated FC_{LOW}.

3.4.5 Low Frequency Response Measurements

1. Measure the FC_{LOW} frequency response using Sine-wave method.
2. Measure the FC_{LOW} frequency response using Square-wave method.
3. Compare the calculated and measured values noting any discrepancies.

3.4.6 Below the Pass-band Output Calculations

1. Show all formulas and steps for calculating the output at frequencies below FC_{LOW}:
   (a) V_{OUT}
   (b) Phase ϕ
   (c) Loss in dB
2. Show all calculations for the output at the following points, including Voltage, Phase, and dB (Use your measured FC_{LOW} value from the previous sub-section):
   (a) FC_{LOW}
   (b) The first *Octave*
   (c) The first *Decade*

3.4.7 Below the Pass-band Output Measurements

1. Measure the output at the following points, including Voltage, Phase, and dB:
   (a) FC_{LOW}
   (b) The first *Octave*
   (c) The first *Decade*
2. Collect calculated and measured data in a table.

3.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 39.
- Include all the data sets referenced in the lab.

3.6 Key Terms

Define The Following:

- Beta
- Alpha
- Decibel
- Mid-range Gain
- Critical Frequency
- Roll-off
- Octave
- Decade
- Bode Plot
- Bandwidth
- Coupling Capacitors & Frequency Response
- Bypass Capacitors & Frequency Response
- Internal Transistor Device Capacitance
- Miller's Theorem

3.7 Key Formulas

- List and define each of the key formulas used in this lab.

3.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

3.9 Table Formatting and Data Sets

Table 3.1: Multi-Stage DC Data

	Calculated	*Measured*		*Calculated*	*Measured*		*Calculated*
VCC			VCE_{Q1}			P_{Q1}	
			VCE_{Q2}			P_{Q2}	
$R1$			V_{R1}			P_{R1}	
$R2$			V_{R2}			P_{R2}	
$R3$			V_{R3}			P_{R3}	
$R4$			V_{R4}			P_{R4}	
$R5$			V_{R5}			P_{R5}	
$R6$			V_{R6}			P_{R6}	
$R7$			V_{R7}			P_{R7}	
$R8$			V_{R8}			P_{R8}	
$R9$			V_{R9}			P_{R9}	
$R10$			V_{R10}			P_{R10}	
$R11$			V_{R11}			P_{R11}	
$R12$			V_{R12}			P_{R12}	

Table 3.2: Multi-Stage AC Data.

	Calculated	*Measured*		*Calculated*	*Measured*
Zin			$Zout$		
Vin_{PP}			$Vout_{pp}$		
ΔV_{Q1}			ΔV_{Q2}		
ΔV_{Total}					
Vin_{MAXp}			$Vout_{MAXp}$		

Table 3.3: Multi-Stage Low Frequency Response Data.

Frequency Response Low, calculated capacitance values for 1KHz.					
	Calculated		*Calculated*	*Std. Value*	$Fc_{LOW}Std.V$
$Rthev_{C1}$		$C1$			
$Rthev_{C2}$		$C2$			
$Rthev_{C3}$		$C3$			
$Rthev_{C4}$		$C4$			
$Rthev_{C5}$		$C5$			
$Rthev_{C6}$		$C6$			
Calculated Fc_{LOW} *using standard value capacitors* $Fc_{LOW}Total$:					
Sine-wave Analysis Measurement:					
				$Fc_{LOW}Total$:	
Square-wave Analysis Measurement:					
$Tilt$		PW		$Fc_{LOW}Total$:	
Phase and dB Calculations and Measurements					
	Freq.	Calc.θ	Meas.θ	Calc. dB	Meas. dB
Fc_{LOW}					
$1^{st}Octave$					
$1^{st}Decade$					

Table 3.4: Multi-Stage Amplifiers Part 1 Check-Off Sheet

RCET 2253 Clinical Assistant Professor Timothy Leishman *Multi-Stage Amplifier* Check-Off Sheet			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
DC Calculations	3.4.1		
AC Calculations	3.4.2		
DC Measurements	3.4.3		
AC Measurements	3.4.3		
Frequency Response Calculations	3.4.4		
Frequency Response Measurements	3.4.5		
$20dB_{Decade}$ Roll-Off	4.4.5		
Instructor Notes:			

Lab 4

Multi-Stage Amplifier: High Critical Frequency and Peaking

4.1 Objectives

Objective A: Calculate and measure the Critical Frequency High of an Amplifier.

- **Frequency Critical High:** Re-Draw that AC equivalent circuit at Frequency Critical High. Draw and Calculate parallel capacitance $Ctotal_{In}$, $Ctotal_{Mid}$, and $Ctotal_{Out}$. Calculate the Thevenin Equivalent Resistances and Frequency Critical High.

Objective B: Improve the Critical Frequency High of an Amplifier Circuit Using Emitter, Shunt, & Series Peaking.

- **Emitter, Shunt, & Series Peaking:** Understand and apply techniques such as emitter peaking, shunt peaking, and series peaking to enhance the high-frequency response of an amplifier circuit. These techniques involve the use of additional components to mitigate the roll-off in gain at high frequencies.

Objective C: Discuss and Show Calculations for Each Circuit Modification, including the predicted Improvement Factor (K).

- **Calculations:** Discuss and demonstrate the mathematical calculations involved in implementing each circuit modification. This includes determining component values and their impact on the amplifier's high-frequency response.

Objective D: Measure, Calibrate, and Document the Results of Each Circuit Modification.

- **Measurement:** Use measurement instruments like an oscilloscope, audio function generator, and a DMM to measure and document the actual performance of the amplifier after each circuit modification.
- **Calibrate:** Calibrate each modification to optimize the pass-band, document the calibration procedure.

- **Record Data** Record calculated, measured, and calibrated data related to gain, frequency response, and other relevant parameters.

Objective E: Identify and Reconcile Any Discrepancies Between a Calculated and Measured Result.

- **Discrepancies:** Analyze the differences between calculated and measured results for each circuit modification. Identify potential sources of error and work to reconcile any disparities between theoretical predictions and experimental observations.

Objective F: Demonstrate the Proper Use of the Oscilloscope, DMM, and Audio Function Generator to Obtain Accurate Measurements.

- **Oscilloscope, DMM, and Sweep Audio Generator:** Continuously emphasize the correct setup and operation of measurement instruments such as oscilloscopes, DMMs, and sweep audio generators. Ensure that students can use these tools effectively to obtain precise measurements and validate circuit modifications.

4.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- Multi-Stage Amplifiers Section 3.

4.3 Checkoff Sheet:

See Table 4.2 *Multi-Stage Amplifier Part 1 Check-Off Sheet* on Page 50.

4.4 Lab Instructions

4.4.1 Frequency Critical High Calculations

1. Note circuit considerations and formulas for calculating FC_{HIGH}.
2. Calculate the following. Show all formulas and steps for calculations:
   (a) $C_{TotalIN}$, $C_{TotalMID}$, $C_{TotalOUT}$
   (b) $RTH_{CTotalIN}$, $RTH_{CTotalMID}$, $RTH_{CTotalOUT}$
   (c) $FC_{TotalIN}$, $FC_{TotalMID}$, $FC_{TotalOUT}$
   (d) FC_{HIGH}

4.4.2 Frequency Critical High Measurements

1. Measure the FC_{HIGH} frequency response using Sine-wave method.
2. Measure the FC_{HIGH} frequency response using Square-wave method.
3. Compare the calculated and measured values noting any discrepancies.
4. Collect the calculated and measured data in a table.

4.4.3 Frequency Critical High adjusted to 1Mhz

1. Modify the circuit by adding parallel capacitance to achieve a new frequency critical high equal to 1Mhz, $Fc_{High} = 1Mhz$.
2. Document procedure, calculations, and measurements.

4.4.4 Above the Pass-band Output Calculations

1. Show all formulas and steps for calculating the output at frequencies beyond FC_{HIGH}:
   (a) V_{OUT}
   (b) Phase ϕ
   (c) Loss in dB
2. Show all calculations for the output at the following points, including Voltage, Phase, and dB (Use your measured FC_{HIGH} value from the previous sub-section):
   (a) FC_{HIGH}
   (b) The first *Octave*
   (c) The first *Decade*

4.4.5 Above the Pass-band Output Measurements

1. Measure Voltage, Phase, and dB for the following:
   (a) FC_{HIGH}
   (b) The first *Octave*
   (c) The first *Decade*
2. Compare the calculated and measured values noting any discrepancies.
3. Collect calculated and measured data in a Table.
4. Section Check-Off:

(a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

(b) Be prepared to answer questions and demonstrate measurements made in this section.

4.4.6 Emitter Peaking Calculations:

1. Explain what Emitter Peaking is and how it works.

   (a) Begin by providing a theoretical explanation of Emitter Peaking in terms of the voltage gain formula: $\Delta v = \frac{Vout}{Vin}$

2. Step through the calculation process to determine the value of the capacitor required for emitter peaking for the Multi-Stage Amplifier.

   (a) Calculate the Emitter Peaking Capacitor (C_{EP}) using the previously adjusted and measured FC_{High}.

   (b) Calculate the new Frequency Critical High (FCH_{EP}).

   (c) Calculate the Emitter Peaking Improvement Factor (K_{EP}).

   (d) Create predicted Emitter Peaking Bode Plot in reference to the original Bode Plot.

4.4.7 Emitter Peaking Measurements

1. Measure/verify FC_{High}.

2. Install the calculated Emitter Peaking Capacitor into the circuit.

3. Using the function generator, sweep the frequency and observe the bode plot response on the oscilloscope.

   - If pre-peaking is observed, adjust C_{EP} capacitance to flatten or calibrate the pass-band. Verify that the pass-band is flat.

4. Measure the new FCH_{EP} and note any changes to C_{EP}.

5. Calculate the measured Emitter Peaking Improvement Factor.

   - If the pass-band is flat but the improvement factor is below expectations, adjust C_{EP} to achieve the proper improvement factor without adding any pre-peaking to the pass-band.

6. Capture the frequency sweep image of the Bode Plot on the Oscilloscope with Cursor 1 set to the pass-band voltage and Cursor 2 set to the -3dB point.

7. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

8. Collect calculated and measured data in a table.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

4.4.8 Shunt Peaking Calculations:

1. Explain what Shunt Peaking is and how it works.

   (a) Begin by providing a theoretical explanation of Shunt Peaking in terms of the voltage gain formula: $\Delta v = \frac{Vout}{Vin}$

2. Step through the calculation process to determine the value of the inductor required for shunt peaking for the Multi-Stage Amplifier circuit.

   (a) Calculate the Shunt Peaking Inductor (L_{ShuntP}) using the previously adjusted and measured FC_{High}.

   (b) Note the Shunt Peaking Optimal Improvement Factor (K_{ShuntP}).

   (c) Calculate the new Frequency Critical High (FC_{HIGH_ShuntP}).

   (d) Create predicted Shunt Peaking Bode Plot in reference to the original Bode Plot.

4.4.9 Shunt Peaking Measurements

1. Measure/verify FC_{High}.

2. Install the calculated Shunt Peaking Inductor into the circuit.

3. Using the function generator, sweep the frequency and observe the bode plot response on the oscilloscope.

   - If pre-peaking is observed, adjust L_{ShuntP} inductance to flatten or calibrate the pass-band. Verify that the pass-band is flat.

4. Measure the new FCH_{ShuntP} and note any changes to L_{ShuntP}.

5. Calculate the measured Shunt Peaking Improvement Factor.

   - If the pass-band is flat but the improvement factor is below expectations, adjust L_{ShuntP} to achieve the proper improvement factor without adding any pre-peaking.

6. Capture the frequency sweep image of the Bode Plot on the Oscilloscope with Cursor 1 set to the pass-band voltage and Cursor 2 set to the -3dB point.

7. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

8. Collect calculated and measured data in a table.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

4.4.10 Series Peaking Calculations:

1. Explain what Series Peaking is and how it works.

   - Begin by providing a theoretical explanation of Series Peaking in terms of "Voltage Magnification".

2. Step through the calculation process to determine the value of the inductor required for series peaking for the Multi-Stage Amplifier circuit.

   (a) Calculate the Series Peaking Inductor (L_{ShuntP}) using the previously adjusted and measured FC_{High}.

   (b) Note the Series Peaking Optimal Improvement Factor ($K_{SeriesP}$).

   (c) Calculate the new Frequency Critical High ($FCH_{SeriesP}$).

   (d) Create predicted Series Peaking Bode Plot in reference to the original Bode Plot.

4.4.11 Series Peaking Measurements

1. Measure/verify FC_{High}.

2. Install the calculated Series Peaking Inductor into the circuit.

3. Using the function generator, sweep the frequency and observe the bode plot response on the oscilloscope.

   - If pre-peaking is observed, adjust $L_{SeriesP}$ inductance to flatten or calibrate the pass-band. Verify that the pass-band is flat.

4. Measure the new $FCH_{SeriesP}$ and note any changes to $L_{SeriesP}$.

5. Calculate the measured Series Peaking Improvement Factor.

- If the pass-band is flat but the improvement factor is below expectations, adjust $L_{SeriesP}$ to achieve the proper improvement factor without adding any pre-peaking.

6. Capture the sweep image of the Bode Plot on the Oscilloscope with Cursor 1 set to the pass-band and Cursor 2 set to the -3dB point.

7. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

8. Collect calculated and measured data in a table.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

4.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 49.
- Include all the data sets referenced in the lab.

4.6 Key Terms

Define The Following:

- Frequency Critical High
- Peaking
- Pre-Peaking
- Emitter Peaking
- Shunt Peaking
- Series Peaking
- Improvement Factor

4.7 Key Formulas

- List and define each of the key formulas used in this lab.

4.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

4.9 Table Formatting and Data Sets

Table 4.1: Multi-Stage Peaking Frequency Response Data.

Sec.4.4.6	FC_{HIGH}	C_{EP}	FCH_{EP}	*Imp.(K)*
Calculated				
Measured				
Sec.4.4.8	FC_{HIGH}	L_{ShuntP}	FCH_{ShuntP}	*Imp.(K)*
Calculated				
Measured				
Sec.4.4.10	FC_{HIGH}	$L_{SeriesP}$	$FCH_{SeriesP}$	*Imp.(K)*
Calculated				
Measured				

Table 4.2: Multi-Stage Amplifiers Part 2 Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

Multi-Stage Amplifier Part 2

Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
FC_{High} *Calculations and Measurement*	4.4.1		
FC_{High} *Calibrated*	4.4.3		
Emitter Peaking Calculations	4.4.6		
Emitter Peaking Measurements	4.4.7		
Shunt Peaking Calculations	4.4.8		
Shunt Peaking Measurements	4.4.9		
Series Peaking Calculations	4.4.10		
Series Peaking Measurements	4.4.11		

Instructor Notes:

Lab 5

Push Pull Class AB Amplifiers

5.1 Objectives

Objective A: Calculate Voltages, Currents, Gains, and Impedances of Push-Pull Amplifier Circuits.

1. **Calculate Voltages and Currents:** Students should be able to perform calculations to determine voltages and currents at various nodes in push-pull amplifier circuits. This involves applying principles of circuit analysis, Ohm's Law, and Kirchhoff's laws.

2. **Calculate Gains:** Understand how to calculate voltage and current gains for push-pull amplifiers.

3. **Calculate Impedances:** Calculate the input and output impedances of push-pull amplifier circuits, taking into account the components and circuit topology.

Objective B: Construct, Measure, and Demonstrate the Proper Use of the Test Equipment.

1. **Construct Push-Pull Amplifier Circuits:** Students should be able to construct practical push-pull amplifier circuits based on provided schematics or design specifications.

2. **Measure with Test Equipment:** Show proficiency in setting up and operating test equipment to obtain accurate measurements. Demonstrate the proper use of test equipment, including oscilloscopes, DMMs, signal generators, and function generators, to measure voltage levels, gains, and impedance values in push-pull amplifier circuits.

3. **Data Collection:** Develop the ability to collect and document data systematically during experimentation. Record measurements accurately, including voltage levels, current values, gains, and impedance values, ensuring that data is organized for analysis.

5.2 Reference Documents:

- Differential Amplifiers Lab Chapter 6.
- Theory Notes
- First Year Text Books
- First Year Laboratory Books

5.3 Checkoff Sheet

See Table ?? *Push Pull Class AB Check-Off Sheet* on Page 59.

5.4 Lab Instructions:

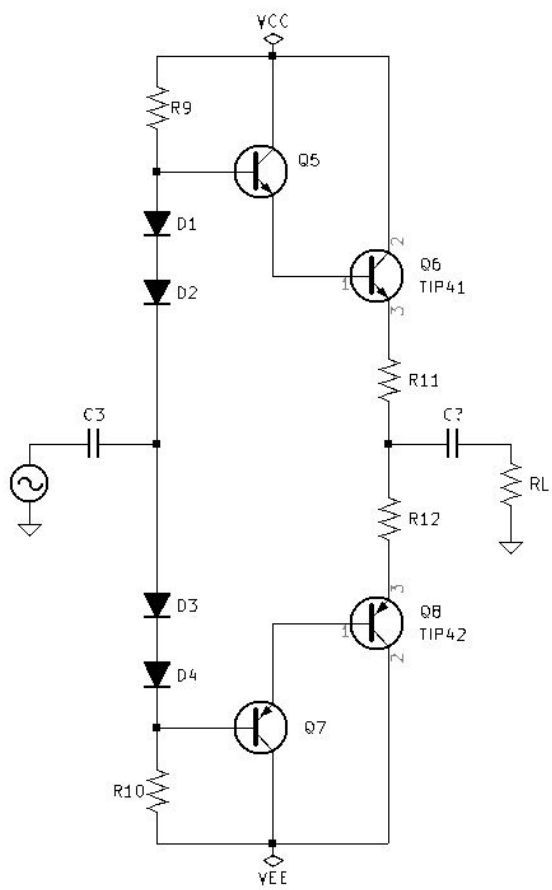


Figure 5.1: Push Pull Amplifier.

5.4.1 Design: Push-Pull Amplifier

1. See Figure 5.1 *Push Pull Amplifier* on page 52.
2. Design Parameters:
   (a) $V_{CC} = 25V$
   (b) $V_{EE} = 0V$
   (c) The Push-Pull must be capable of driving an 8Ω, 5 watt load.
   (d) Frequency Response capability of 20hz to 20Khz.
3. Include a properly labeled schematic.
4. Including the following calculations:
   - resistors
   - voltages
   - powers
   - capacitors
   - $Vout_{P\_max}$
   - Vin_{P_max}
   - Z_{in}
   - Z_{out}
   - heat sinks
5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.4.2 Cross-Over Distortion Measurement Procedure

1. Cross-Over Distortion Measurement:
   (a) Define Cross-Over Distortion & Draw a predicted image of Cross-Over Distortion in your Lab Book.
   (b) Build your calculated Push-Pull Amplifier with D2 and D4 removed from the circuit. Also, replace RL with a $10K\Omega$ resistor. See Figure 5.2 *Push Pull Amplifier Cross-Over Distortion Test Circuit.* on page 54.
   (c) Apply the DC voltages V_{CC} & V_{EE} to the circuit.
   (d) Measure DC voltages. Verify that $VR11$ & $VR12$ measure 0VDC. If you find that R11 & R12 still have a small amount of voltage (mill-volts), remove the remaining biasing diodes D1 and D3 from the circuit.

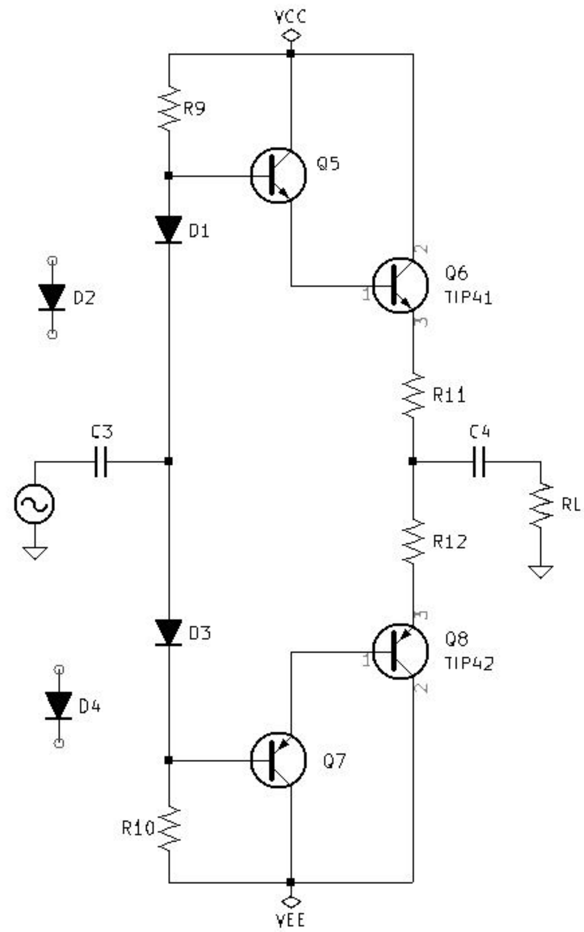


Figure 5.2: Push Pull Amplifier Cross-Over Distortion Test Circuit.

(e) Start with $RL = 10K\Omega$, connect a $9vp$ AC waveform to the input of the circuit.

(f) Observe and document the Cross-Over Distortion. Note the voltage gain.

- If Cross-Over is not overly apparent, adjust RL to $\approx 8\Omega$ making sure RL has the appropriate power rating and Q6 & Q8 have the appropriate heat sinks. Document the input and output waveforms.

(g) Observe and measure the Cross-Over distortion using oscilloscope waveform measurements.

(h) Observe and measure the Cross-Over distortion using Lissajous measurements.

(i) Observe and measure the Cross-Over (harmonic) distortion using FFT.

Section Check-Off:

2. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.4.3 Push-Pull Circuit Calibration Procedure

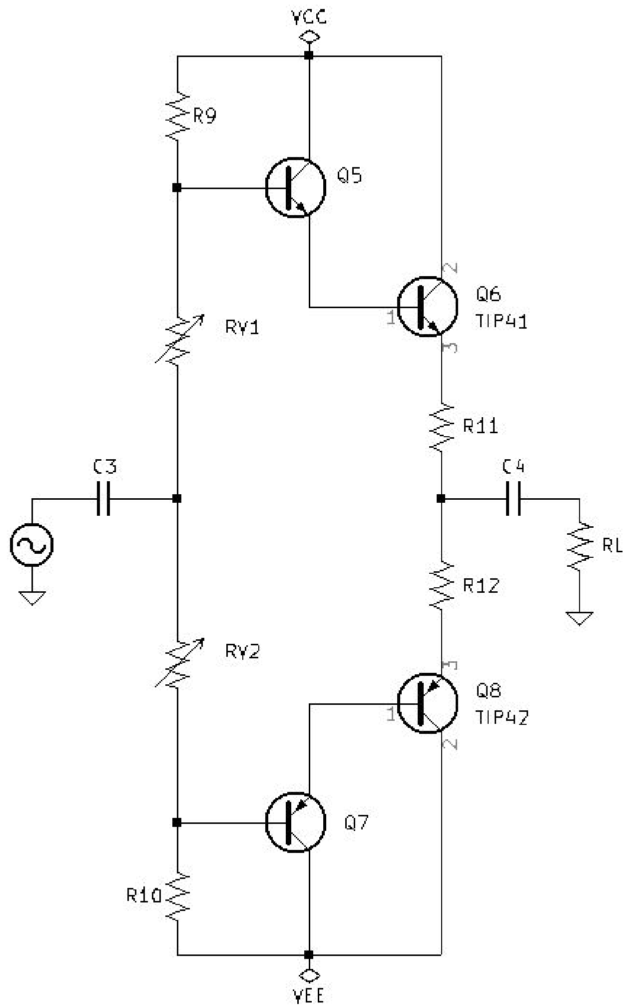


Figure 5.3: Push Pull Amplifier Calibration Circuit.

1. Define Shoot-Through in terms of Push-Pull amplifiers.

2. Define Quiescent Current in terms of Push-Pull amplifiers.

3. The goal of Push-Pull Circuit Calibration is to eliminate the Cross-Over Distortion by adjusting the biasing to achieve a slight amount of acceptable quiescent current when a 0v input signal is applied. Too much quiescent current may cause shoot-through, which will damage the circuit components, and not enough will cause excessive crossover distortion.

4. Check the circuit for a minimum amount of quiescent by tying the input to ground and measuring the DC voltage across R11 and R12. At this point, R11 and R12 should have 0v. If milli-volts are measured repeat the steps in section 5.4.2.

5. See Figure 5.3 *Push Pull Amplifier Calibration Circuit* on page 55.

6. (Use the current limiting control on the power supply when performing this step) Adjust the bias resistors to provide approximately 30mA of quiescent current: $I_{quiescent} \approx 30mA$.

7. Verify the following (making sure to use appropriate heat sinks and resistor power ratings):

   (a) The circuit operates across a range of loads. Incrementally decrease and test the circuit load with the final load of 8 ohms, $RL = 8\Omega$.

   (b) Cross-Over distortion is no longer observable at $RL = 8\Omega$. Document the measured input and output waveforms, and include Lissajous and FFT measurements.

   (c) Measure $VoutP_{Max}$ using both the traditional waveform method (observing hard clipping) and FFT (observing harmonic content).

8. Collect calculated and measured data in a Table.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.4.4 Push-Pull Frequency Response Test

1. With the input signal set to $1v_{PP}$ and the load RL equal to 8 ohms, use square wave analysis to measure the frequency response of the Push-Pull amplifier.

2. Verify the circuit can provide the full audio range of 20hz or less to 20Khz or more. Make the necessary circuit adjustments and repeat the frequency response measurements.

3. Collect calculated and measured data in a Table.

4. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.4.5 Design: Single Stage, Universal Biased, Common Emitter Amplifier

1. Design an Optimized Universal Biased Common Emitter NPN BJT Amplifier with a supply voltage of 25V.
2. Using the Oscilloscope, measure the maximum peak output voltage of a BlueTooth module connected to your phone at maximum volume (make sure the oscilloscope is in sample mode, not averaging).
3. Determine the necessary voltage gain needed to provide 5 watts of power to an 8Ω load ($\Delta v \approx -10$).
4. Verify $VoutP_{Max}$ of the Single Stage Amplifier ($\approx 9vp$).
5. Verify the Frequency Response of the Single Stage Amplifier (20hz to 20Khz).

5.4.6 Single Stage with Push-Pull, 5-watt Load Test

1. Verify power calculations and include Heat-Sink calculations for the Tip41 & Tip42.
2. With proper heat sinks installed, replace RL with an 8Ω resistor with an appropriate power rating.
3. Set the Function Generator input signal to $1v_{PP}$ and observe the output. Slowly increase the input signal while observing the signal at the load. Increase the signal until the load achieves 5 watts. Verify that the circuit is capable of providing a non-distorted 5-watt signal to an 8Ω load.
4. Collect calculated and measured data in a table.
5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.4.7 Speaker Test

1. Replace the Audio Function Generator with BlueTooth receiver.
2. Replace the 8Ω Load with an 8Ω speaker.
3. Play music, verify that the audio level at maximum volume is at or near 5 watts. Adjust the circuit voltage gain as needed.
4. Play the song *Orange Blossom Special*.

5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

5.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 58.
- Include all the data sets referenced in the lab.

5.6 Key Terms

Define The Following:

- Class AB Amplifier
- Push-Pull Amplifier
- Head Room
- Cross-Over Distortion
- Shoot-Through
- Audible Frequency Range

5.7 Key Formulas

- List and define each of the key formulas used in this lab.

5.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

5.9 Check-Off Sheet

RCET 2252
Clinical Assistant Professor
Timothy Leishman

Push Pull Class AB Amplifiers
Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
Push-Pull Amplifier Calculations	5.4.1		
Cross-Over Distortion Measurements	5.4.2		
Push-Pull Circuit Calibration	5.4.3		
Push-Pull Frequency Response	5.4.4		
Push-Pull 5-watt Load Test	5.4.6		
Single-Stage & Push-Pull: 8Ω ΔV and Freq.	5.4.6		
Speaker Test - Orange Blossom Special	5.4.7		

Instructor Notes:

Lab 6

Differential Amplifiers

6.1 Objectives

Objective A: Calculate Voltages, Currents, Gains, and Common Mode Rejection Ratio for Differential Amplifier Circuits.

1. **Calculate Voltages and Currents:** Students should be able to perform calculations to determine voltages and currents at various nodes in differential amplifier circuits. This involves applying principles of circuit analysis, Ohm's Law, and Kirchhoff's laws.

2. **Calculate Gains:** Understand how to calculate voltage or current gains for differential amplifiers. This includes single-ended gains (inverting and non-inverting) differential gain (gain for differential input), and common-mode gain (gain for common-mode input).

3. **Calculate Common Mode Rejection Ratio (CMRR):** Calculate the CMRR, which quantifies the ability of a differential amplifier to reject common-mode signals while amplifying differential signals.

Objective B: Construct, Measure, and Demonstrate the Proper Use of the Test Equipment.

1. **Construct Differential Amplifier Circuits:** Students should be able to construct practical differential amplifier circuits based on provided schematics or design specifications.

2. **Measure with Test Equipment:** Demonstrate the proper use of test equipment, including oscilloscopes, DMMs, signal generators, and function generators, to measure voltage levels, currents, gains, and other relevant parameters in differential amplifier circuits.

3. **Demonstrate Equipment Usage:** Show proficiency in setting up and operating test equipment to obtain accurate measurements. This includes setting appropriate voltage and current ranges, time scales, and trigger settings on oscilloscopes.

6.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books

6.3 Checkoff Sheet:

See Table 6.3 *Differential Amplifiers Check-Off Sheet* on Page 71.

6.4 Lab Instructions:

6.4.1 Differential Amplifier with Tail Resistor Calculations

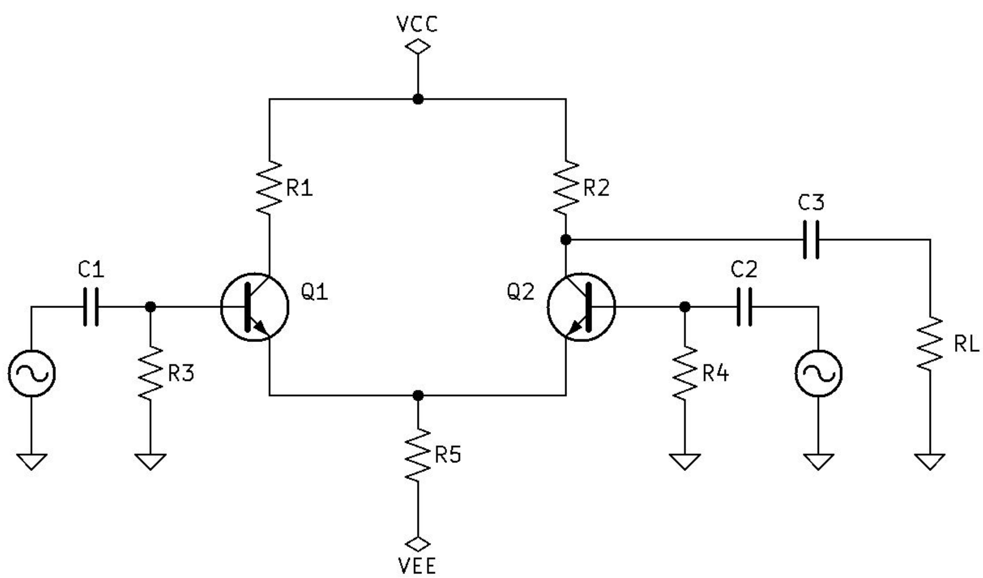


Figure 6.1: Differential Amplifier with Tail Resistor

1. Design a Differential Amplifier with a Tail Resistor using the following parameters:
   (a) See Figure 6.1
   (b) $VCC = 20V_{DC}$ & $VEE = -20V_{DC}$
   (c) Biasing must be optimized at $45\%, 45\%, 10\%$.
   (d) Use two 2N3904 transistors that will operate at 80% of maximum power.

(e) Make the load resistance ten times larger than Z_{OUT}, $(RL = RC \times 10)$.

(f) Calculate all DC voltages and currents.

(g) Calculate the following gains:

- Single-Ended Non-Inverting Gain.
- Single-Ended Inverting Gain.
- Common Mode Gain.
- Differential Mode Gain.

6.4.2 Differential Amplifier with Tail Resistor Measurements

1. Measure all the DC values and verify that the biasing is correct. Make circuit adjustments as needed to correct the biasing voltage. Document any circuit changes and all measured DC voltages.

2. Measure the following gains:

   - Single-Ended Non-Inverting.
   - Single-Ended Inverting.
   - Common Mode.
   - Differential Mode.

3. Calculate the Common Mode Rejection Ratio of the amplifier using the measured values.

4. Create a Table and document all Calculated and measured values.

5. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

   Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

6.4.3 Differential Amplifier with Constant Current Source Calculations

1. Design a Differential Amplifier with a Constant Current Source using the following parameters (same as the previous section):

   (a) See Figure 6.2

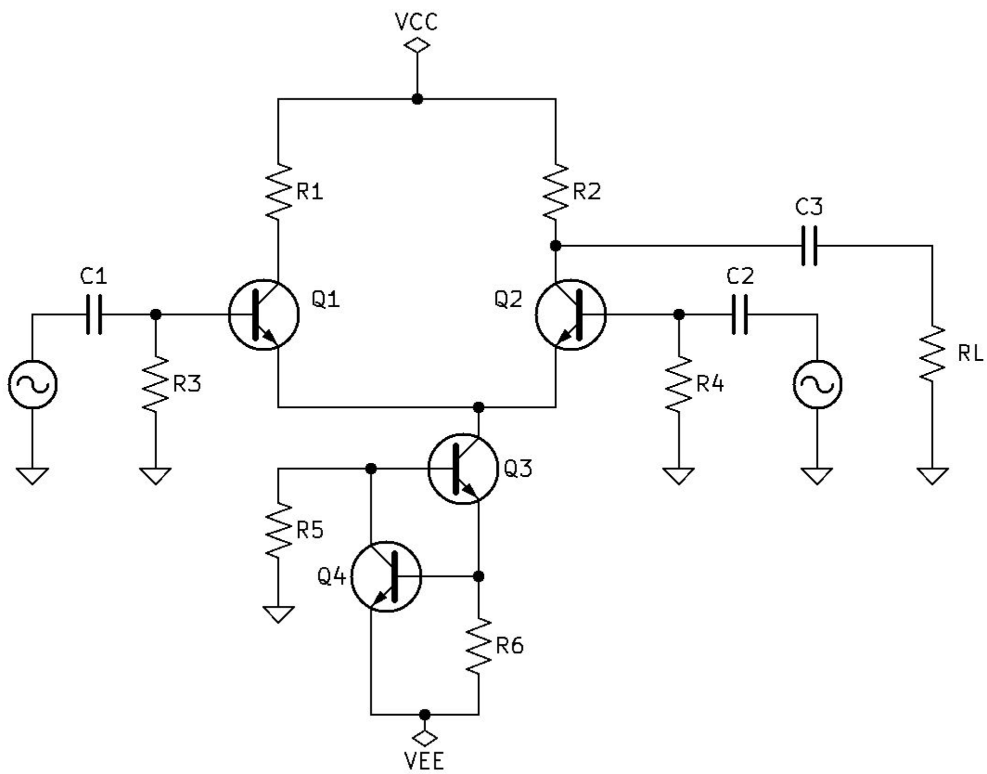


Figure 6.2: Differential Amplifier with Constant Current Source

(b) $VCC = 20V_{DC}$ & $VEE = -20V_{DC}$

(c) Biasing must be optimized at $45\%, 45\%, 10\%$.

(d) Use two 2N3904 transistors that will operate at 80% of maximum power.

(e) Make the load resistance ten times larger than Z_{OUT}, $(RL = RC \times 10)$.

(f) Calculate all DC voltages and currents.

(g) Calculate the following gains:

- Single-Ended Non-Inverting Gain.
- Single-Ended Inverting Gain.
- Common Mode Gain.
- Differential Mode Gain.

6.4.4 Differential Amplifier with Constant Current Source Measurements

1. Measure all the DC values and verify that the biasing is correct. Make circuit adjustments as needed to correct the biasing voltage. Document any circuit changes and all measured DC voltages.

2. Measure the following gains:

- Single-Ended Non-Inverting.
- Single-Ended Inverting.
- Common Mode.
- Differential Mode.

3. Calculate the Common Mode Rejection Ratio of the amplifier using the measured values.

4. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

5. Compare and Contrast the Differential Amplifier with a Tail Resistor and the Differential Amplifier with the Constant Current Source being sure to note advantages and disadvantages.

   Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

6.4.5 Single-Ended Differential Amplifier with Gain Control

1. See Figure 6.3 *Single-Ended Inverting Diff Amp with Gain Control.*

2. Explain how the output signal gain is controlled.

3. Using your previously designed circuit, calculate R7 and R8 values that will provide a voltage gain of -10 ($\Delta_V = -10$).

4. Assemble the circuit and measure the Single-Ended Non-Inverting Gain.

5. Measure $Vout_{maxP}$.

6. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

1. See Figure 6.4 *Single-Ended Non-Inverting Diff Amp with Gain Control.*

2. Explain how the output signal gain is controlled.

3. Using your previously designed circuit, calculate R7 and R8 values that will provide a voltage gain of -10 ($\Delta_V = -10$).

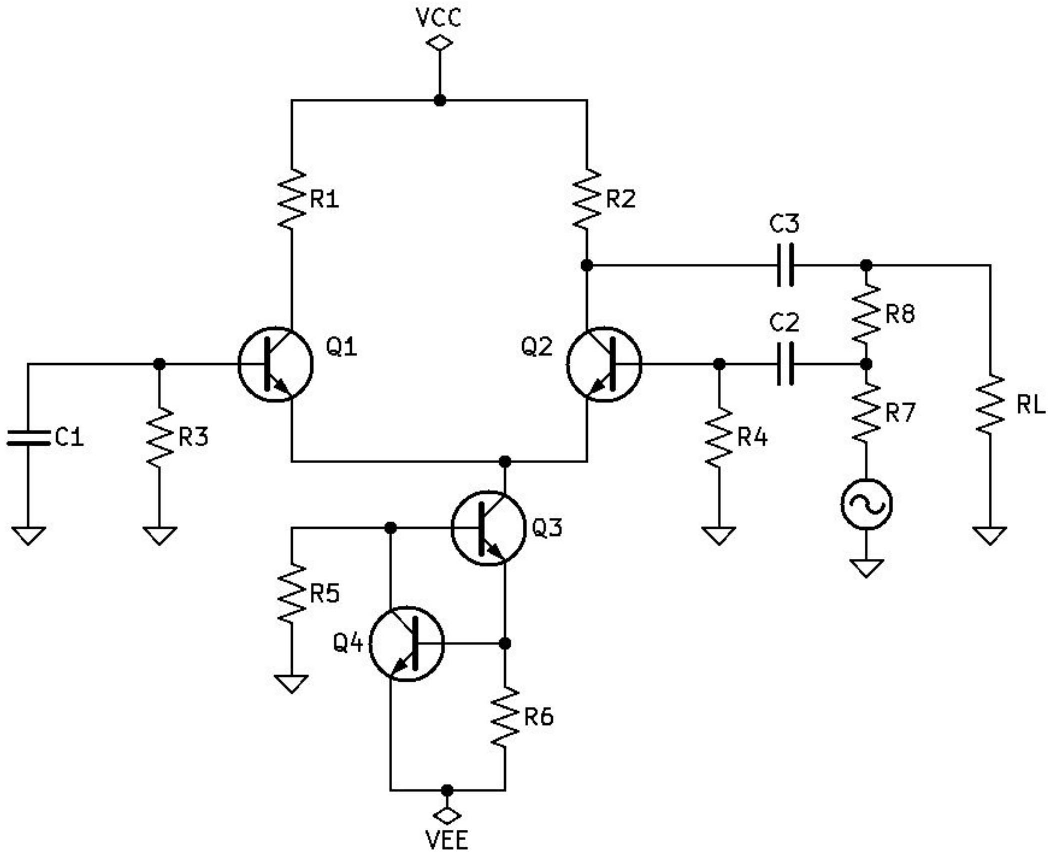


Figure 6.3: Single-Ended Inverting Diff Amp with Gain Control.

4. Assemble the circuit and measure the Single-Ended Inverting Gain.
5. Measure $Vout_{maxP}$.
6. Analyze the data and identify any differences between your calculated and measured results. Think critically about potential sources of error in your practical setup and provide explanations for these discrepancies.

   Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

6.4.6 Differential Amplifier Frequency Response

1. Setup the Single-Ended Non-Inverting Diff Amp with a gain $\Delta_V = 10$.
2. Use Square-Wave Analysis to determine FC_{LOW} & FC_{HIGH} of the amplifier.

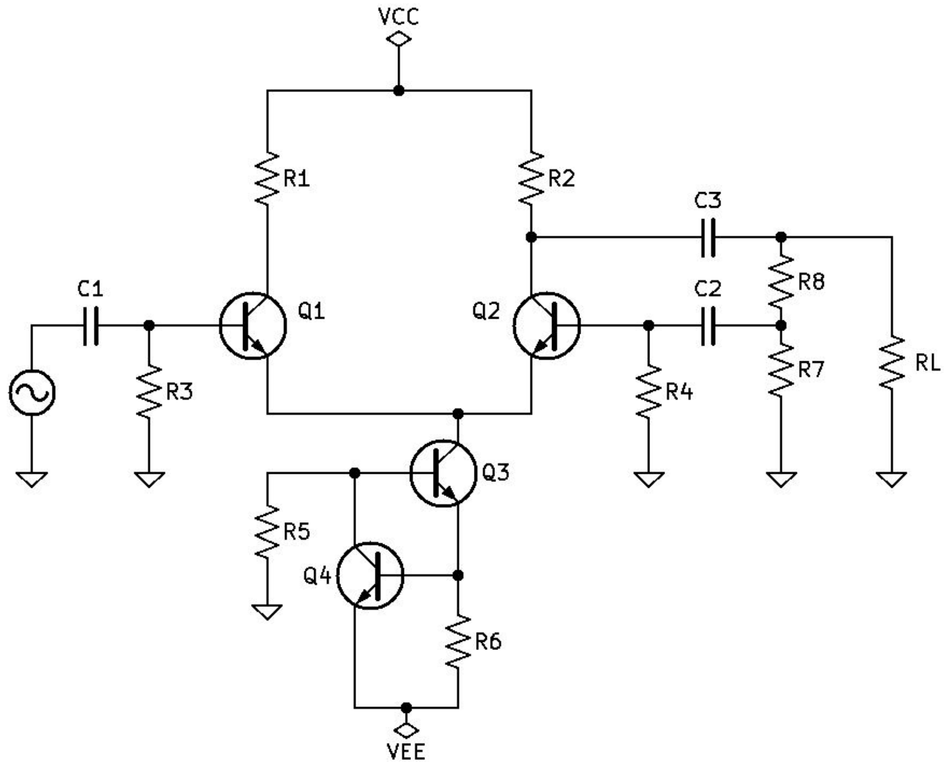


Figure 6.4: Single-Ended Non-Inverting Diff Amp with Gain Control.

3. Repeat the measurement for the Single-Ended Inverting Diff Amp with a gain of $\Delta_V = -10$.

4. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

6.4.7 Differential Amplifier with Push-Pull

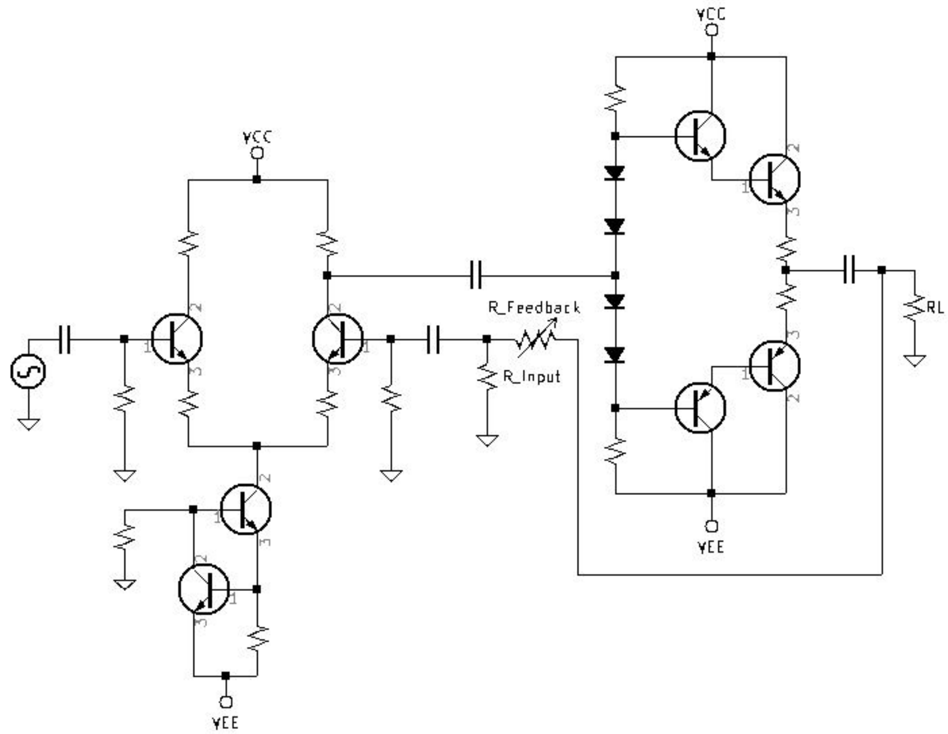


Figure 6.5: Differential Amplifier with Push-Pull Amplifier

1. Modify your previous Push-Pull amplifier to operate using the same split rail voltage as the diff amp. Calibrate the Push-Pull amplifier to have a quiescent current of $\approx 30mA$.

2. Connect the output of the diff amp to the push-pull and run the feedback from the output.

3. Verify amplifier operation using an 8Ω load.

   - Frequency Response
   - Gain and $Vout_{maxp}$
   - Use FFT to observe any harmonic distortion.

4. Disconnect the Diff-Amp and R-Feedback from the Push-Pull. De-tune or remove the quiescent current from the push-pull amplifier and verify that cross-over distortion appears. Use FFT to observe the harmonic distortion. Document the FFT distortion.

5. Reconnect the Push-Pull to the Diff-Amp with the R-Feedback. Observe the harmonic distortion. Did the Diff-Amp improve the cross-over distortion?

6. Adjust the amplifier as needed to minimize any remaining cross-over distortion.
7. Once the amplifier is fully calibrated, you can test using a speaker and Bluetooth audio source. Adjust gain as needed.

6.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 69.
- Include all the data sets referenced in the lab.

6.6 Key Terms

Define The Following:

- Common-Collector (CC)
- Common-Base (CB)
- Common-Emitter (CE)
- Differential Amplifier
- Single-Ended Non-Inverting
- Single-Ended Inverting
- Differential Mode
- Common Mode
- Common Mode Rejection Ratio (CMRR)
- Constant Current Source

6.7 Key Formulas

- List and define each of the key formulas used in this lab.

6.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

6.9 Table Formatting and Data Sets

Table 6.1: Differential Amplifier with Tail Resistor Circuit Data.

Sec.6.4.1 R_{Tail}	V_{CC}	V_{EE}	V_{RC}	V_{CE}	V_{RTail}
Calculated					
Measured					
Sec.6.4.1 R_{Tail}	$R1$ & $R2$	$R3$ & $R4$	$R5$	RL	
Calculated					
Measured					
Sec.6.4.1 R_{Tail}	P_{R1} & P_{R2}	P_{R3} & P_{R4}	P_{R5}	P_{RL}	P_{Q1} & P_{Q2}
Calculated					
Measured					
Sec.6.4.2 R_{Tail}	Z_{IN}	Z_{OUT}	ΔV_{CE}	ΔV_{CC}	ΔV_{CB}
Calculated					
Measured					
Sec.6.4.2 R_{Tail}	ΔV_{CCCB}	ΔV_{CM}	ΔV_{Diff}	$CMRR$	$CMRR_{dB}$
Calculated					
Measured					

Table 6.2: Differential Amplifier with Constant Current Source Circuit Data.

Sec.6.4.3 CCS	V_{CC}	V_{EE}	V_{RC}	V_{CE}	V_{CCS}
$Calculated$					
$Measured$					
Sec.6.4.3 CCS	$R1$ & $R2$	$R3$ & $R4$	$R5$	$R6$	RL
$Calculated$					
$Measured$					
Sec.6.4.3 CCS	P_{R1} & P_{R2}	P_{R3} & P_{R4}	P_{R5}	P_{R6}	
$Calculated$					
$Measured$					
Sec.6.4.3 CCS	P_{Q1} & P_{Q2}	P_{Q3}	P_{Q4}		
$Calculated$					
$Measured$					
Sec.6.4.3 CCS	Z_{IN}	Z_{OUT}	ΔV_{CE}	ΔV_{CC}	ΔV_{CB}
$Calculated$					
$Measured$					
Sec.6.4.3 CCS	ΔV_{CCCB}	ΔV_{CM}	ΔV_{Diff}	$CMRR$	$CMRR_{dB}$
$Calculated$					
$Measured$					
Sec.6.4.5 CCS	$\Delta V-$	$\Delta V+$	$Vout_{maxP}$	FC_{LOW}	FC_{HIGH}
$Calculated$	-10	+10		20hz	20Khz
$Measured$					

Table 6.3: Differential Amplifiers Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

Differential Amplifiers

Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
Diff Amp with R_{Tail} Calculations	6.4.1		
Diff Amp with R_{Tail} Measurements	6.4.2		
Diff Amp with CCS Calculations	6.4.3		
Diff Amp with CCS Measurements	6.4.4		
Diff Amp with Gain Control	6.4.5		
Diff Amp Frequency Response	6.4.6		
Instructor Notes:			

Lab 7

Operational Amplifiers

7.1 Objectives

Objective A: Calculate Voltages, Currents, Gains, Slew Rate, Frequency Response, Input and Output Impedances, and Common Mode Rejection Ratio for Operational Amplifier Circuits.

1. **Calculate Voltages and Currents:** Students should be proficient in calculating voltages and currents at various points of operational amplifier circuits. This includes applying fundamental circuit analysis principles and using Ohm's Law and Kirchhoff's laws.

2. **Calculate Gains:** Understand how to calculate voltage and current gains for push-pull amplifiers.

3. **Define Slew Rate:** Define Slew Rate and use a data sheet to identify Slew Rate specifications.

4. **Frequency Response:** Determine the frequency response of an Operational Amplifier circuit.

5. **Impedances Z_{IN} & Z_{OUT} :** Calculate the input and output impedances of an Operational Amplifier circuit.

6. **Common Mode Rejection Ratio:** Calculate the Common Mode Rejection Ratio of an Operational Amplifier in decibels.

Objective B: Construct, Measure, and Demonstrate the Proper Use of the Test Equipment.

1. **Construct Operational Amplifier Circuits:** Students should be capable of building practical operational amplifier circuits according to provided schematics or design specifications.

2. **Measure with Test Equipment:** Show proficiency in setting up and operating test equipment to obtain accurate measurements. Demonstrate the proper use of test equipment, including oscilloscopes, DMMs, signal generators, and function generators, to measure voltage levels, gains, and frequency response of operational amplifier circuits.

3. **Data Collection:** Develop the ability to collect and document data systematically during experimentation. Record measurements accurately, including voltage levels, current values, gains, and frequency response values, ensuring that data is organized for analysis.

7.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- TL071 Datasheet [9]
- MCP6002 Datasheet [10]

7.3 Checkoff Sheet:

See Table 7.7 *Operational Amplifier Check-Off Sheet* on Page 81.

7.4 Lab Instructions:

7.4.1 Operational Amplifier General Information

1. List the Ideal Characteristics of an Operational Amplifier.
2. Show the Basic Internal Arrangement of an Operational Amplifier.
3. Document in your lab book the two rules for calculating an Operational Amplifier circuit.
4. Document in your lab book the specific steps used for calculating an Operational Amplifier circuit output voltage.
5. Show, label, and provide a theory of operation for the following operational amplifier circuits:

(a) Non-Inverting
(b) Inverting
(c) Common Mode
(d) Differential Mode

6. Define the following:

   (a) Δ_{OL} Open Loop
   (b) Δ_{CM} Common Mode
   (c) $CMRR$
   (d) $SlewRate$
   (e) FAB
   (f) GBW
   (g) FC_{LOW} & FC_{HIGH}
   (h) Z_{IN} & Z_{OUT}

7.4.2 Slew Rate Measurements

1. Document the slew rate specification for a LM741 Operational Amplifier. See the *LM741 Data Sheet* [11].

2. Document the slew rate specification for a TL071 Operational Amplifier. See the *TL071 Data Sheet* [9].

3. Build a circuit to measure the slew rate of TL071 operational amplifier. Document test procedure and measured waveforms.

4. Document the slew rate specification for a MCP6002 Operational Amplifier. See the *MCP6002 Data Sheet* [10].

5. Build a circuit to measure the slew rate of MCP6002 operational amplifier. Document test procedure and measured waveforms.

6. Collect data. See Table 7.1 *Slew Rate Calculated and Measured Data* on page 78.

7. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.4.3 Differential Amplifier

1. Design an Op-Amp Differential Amplifier to match the gains of the Transistor Differential Amplifier you built and measured in Section 6.4.4. Compare the common mode and differential mode gains, and the CMRR of both circuits.

2. Collect data. See Table 7.2 *Differential Amplifier Comparison Calculated and Measured Data* on page 78.

3. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.4.4 Op-Amp Frequency Response

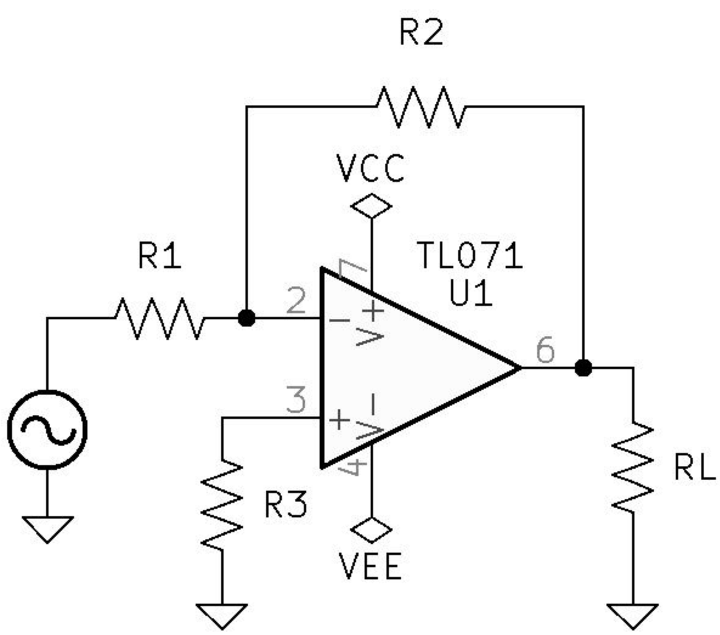


Figure 7.1: Inverting Operational Amplifier Circuit

1. See Figure 7.1 *Inverting Operational Amplifier Circuit.*
2. Calculate the necessary circuit components and frequency response for a Single-Stage Operational Amplifier with the following design specifications:
   (a) $\Delta V = -425$
   (b) $V_{IN} = 60mV_{PP}$
3. Show all circuit calculations.
4. Calculate the Frequency Response of the amplifier.
5. Build and measure the circuit.

6. *Two-Stage* repeat steps 2-5 adding a second op-amp stage (one inverting and one non-inverting).

7. *Three-Stage* repeat steps 2-5 adding a third op-amp stage (one inverting, one non-inverting, and one your choice!).

8. Collect data. See Tables 7.3 thru 7.6 starting on page 79.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.4.5 Operational Amplifiers Z_{IN} & Z_{OUT}

1. List the define the formulas for calculating Z_{IN} & Z_{OUT} for both inverting and non-inverting operational amplifiers.

2. Show Z_{IN} & Z_{OUT} calculations for the three-stage amplifier in section 7.4.4.

7.4.6 Operational Amplifier Loading

1. According to the datasheet for the TL071 [10], what is the typical short-circuit current?

2. Replace RL with a 10Ω resistor in the three-stage Operational Amplifier from section 7.4.4 and measure the output signal.

3. Derive the measured short-circuit current from the measured output signal.

4. Adapt the circuit, using previous knowledge acquired in Push-Pull amplifier lab, to drive a 10Ω load. (Do not build) Provide the schematic and circuit descriptions.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.4.7 Operational Amplifier Comparators

1. Design a circuit using op-amp comparators to light a single LED when the range of VDD specifications is exceeded for the MCP6002 operational amplifier. LED will light when the input voltage drops below the minimum VDD voltage. LED will be off when VDD is in range. LED will light when the input voltage goes above the maximum VDD. Reference the MCP6002 data sheet [10].
2. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.4.8 Voltage Bounding

1. Design a circuit using a TL071 that will convert a wide range of square-wave input signals to TTL levels. Do not exceed the input voltage specifications of the TL071. Reference the TL071 data sheet [9].
2. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

7.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 78.
- Include all the data sets referenced in the lab.

7.6 Key Terms

Define The Following:

- Ideal Op-Amp
- *Slew Rate*
- Rail to Rail
- Δ_{OL}
- FAB
- $GBWP$
- Comparator
- Voltage Bounding

7.7 Key Formulas

- List and define each of the key formulas used in this lab.

7.8 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

7.9 Table Formatting and Data Sets

Table 7.1: Slew Rate Calculated and Measured Data (Section 7.4.2).

Section.7.4.2	$LM741$	$TL071$	$MCP6002$
Data Specification			
Measured			

Table 7.2: Differential Amplifier Comparison Calculated and Measured Data (Section 7.4.3).

Transistor Diff-Amp	ΔV_{CE}	ΔV_{CCCB}	ΔV_{CM}	ΔV_{Diff}	$CMRR_{dB}$
Measured					
TL071 Op Amp	$\Delta V-$	$\Delta V+$	ΔV_{CM}	ΔV_{Diff}	$CMRR_{dB}$
Calculated					
Measured					

Table 7.3: Single-Stage Op-Amp circuit Data (Section 7.4.4).

Single-Stage	$R1$	$R2$	$R3$	RL	
Calculated					
Measured					
Single-Stage	VCC	VEE	V_{IN}	V_{OUT}	ΔV
Calculated					
Measured					

Table 7.4: Two-Stage Op-Amp circuit Data (Section 7.4.4).

Two-Stage	$R1$	$R2$	$R3$	$R4$	$R5$
Calculated					
Measured					
Two-Stage	$R6$	RL	VCC	VEE	V_{IN}
Calculated					
Measured					
Two-Stage	V_{OUT_U1}	V_{OUT_U2}	ΔV_U1	ΔV_U2	ΔV_Total
Calculated					
Measured					

Table 7.5: Three-Stage Op-Amp circuit Data (Section 7.4.4).

Three-Stage	$R1$	$R2$	$R3$	$R4$	$R5$
Calculated					
Measured					
Three-Stage	$R6$	$R7$	$R8$	$R9$	RL
Calculated					
Measured					
Three-Stage	VCC	VEE	V_{OUT_U1}	V_{OUT_U2}	V_{OUT_U3}
Calculated					
Measured					
Two-Stage	ΔV_U1	ΔV_U2	ΔV_U3	ΔV_Total	
Calculated					
Measured					

Table 7.6: Op-Amp multi-stage Frequency vs. Gain Data (Section 7.4.4).

Section 7.4.4	$Single - Stage$	$Two - Stage$	$Three - Stage$
ΔV_Total *Calculated*			
ΔV_Total *Measured*			
FC_{LOW} *Calculated*			
FC_{LOW} *Measured*			
FC_{HIGH} *Calculated*			
FC_{HIGH} *Measured*			

Table 7.7: Multi-Stage Amplifiers Part 1 Check-Off Sheet

RCET 2252 Clinical Assistant Professor Timothy Leishman *Operational Amplifiers* Check-Off Sheet			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
Slew Rate Measurements	7.4.2		
Differential Amplifier Measurements	7.4.3		
Op-Amp Frequency Response	7.4.4		
Op-Amp Loading	7.4.6		
Op-Amp Comparator	7.4.7		
Voltage Bounding	7.4.8		
Instructor Notes:			

Lab 8

Operational Amplifiers: DAC, ADC, & Active Filtering

8.1 Objectives

Objective A: Calculate Analog-to-Digital and Digital-to-Analog Circuits Using Operational Amplifiers.

1. **Digital-to-Analog Circuits**: Understand how to calculate and design circuits that convert digital data into analog signals, employing operational amplifiers. This includes techniques for digital-to-analog conversion and signal reconstruction.
2. **Analog-to-Digital Circuits**: Students should be able to calculate and design circuits that convert analog signals into digital form using operational amplifiers. This may involve concepts like analog-to-digital conversion, signal conditioning, and quantization.

Objective B: Calculate Active Filtering Circuits Using Operational Amplifiers.

1. **Active Filtering Circuits**: Students should be proficient in the calculation and design of active filtering circuits using operational amplifiers. This includes the analysis of filter transfer functions, component selection, and filter response characteristics.

Objective C: Construct and Measure Designed Circuits. Demonstrate the Proper Use of Test Equipment.

1. **Circuit Construction**: Demonstrate the ability to construct the designed circuits for analog-to-digital conversion, digital-to-analog conversion, and active filtering. Follow the provided schematics or design specifications.
2. **Circuit Measurement**: Utilize test equipment, such as oscilloscopes, digital multimeters (DMMs), signal generators, and function generators, to measure and verify the performance of the constructed circuits. This includes measuring key parameters like signal levels, bandwidth, and frequency response.

3. **Equipment Proficiency**: Show proficiency in setting up and using test equipment to ensure accurate measurements. This involves configuring appropriate voltage and current ranges, time scales, and trigger settings on oscilloscopes.

4. **Data Collection**: Develop the ability to systematically collect and record data during experimentation. Accurately document measurements, including voltage levels, currents, gains, and other relevant parameters, ensuring organized data for analysis.

8.2 Reference Documents

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- TL071 Datasheet [9]
- MCP6002 Datasheet [10]

8.3 Checkoff Sheet

See Table ?? *XX Check-Off Sheet* on Page ??.

8.4 DAC & ADC

8.4.1 Digital to Analog Converter (DAC)

1. The Engineering Department has sent you a DAC prototype circuit that they are working on. The DAC circuit is not working as expected. The Engineering Department needs you to analyze the circuit and make sure all the connections are correct. See Figure 8.1 *DAC Engineering Department Prototype Circuit* on page 84.

   (a) Define Digital to Analog Conversion.

   (b) Analyze U1, U2, U3, U4, & U5. Include function, key features, and specifications.

   (c) Calculate resistor values, circuit currents, voltages, and waveforms.

   (d) Draw predicted waveforms at TP1 and TP2.

   (e) Note any circuit corrections.

2. Build and measure the circuit.

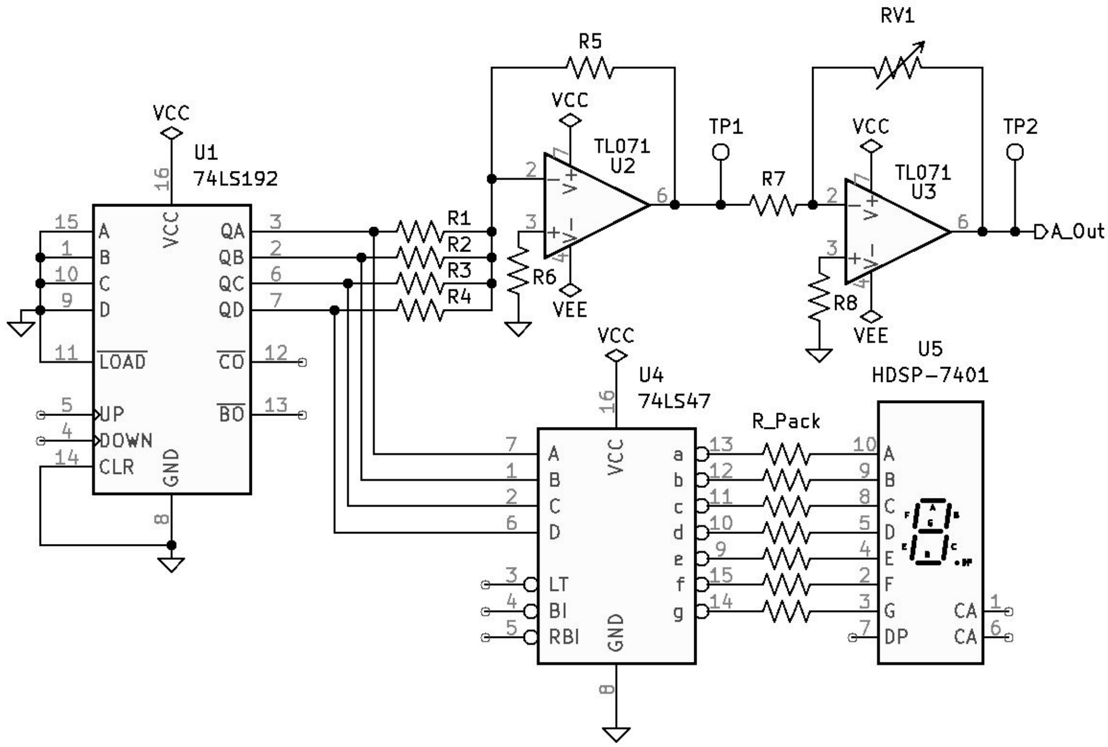


Figure 8.1: DAC Engineering Department Prototype Circuit.

8.4.2 Analog to Digital Converter (ADC)

1. The Engineering Department has sent you an ADC prototype circuit that they are working on. The ADC circuit is not working as expected. The Engineering Department needs you to analyze the circuit and make sure all the connections are correct. See Figure 8.2 *ADC Engineering Department Prototype Circuit* on page 85.

   (a) Define Analog to Digital Conversion.

   (b) Analyze U6, U7, U8, U9, U10, & U1. Include function, key features, and specifications.

   (c) Calculate resistor values, circuit currents, voltages, and waveforms.

   (d) Note any circuit corrections.

2. Build and measure the circuit, connecting the Analog Out of the DAC circuit to the Analog In of the ADC circuit.

3. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

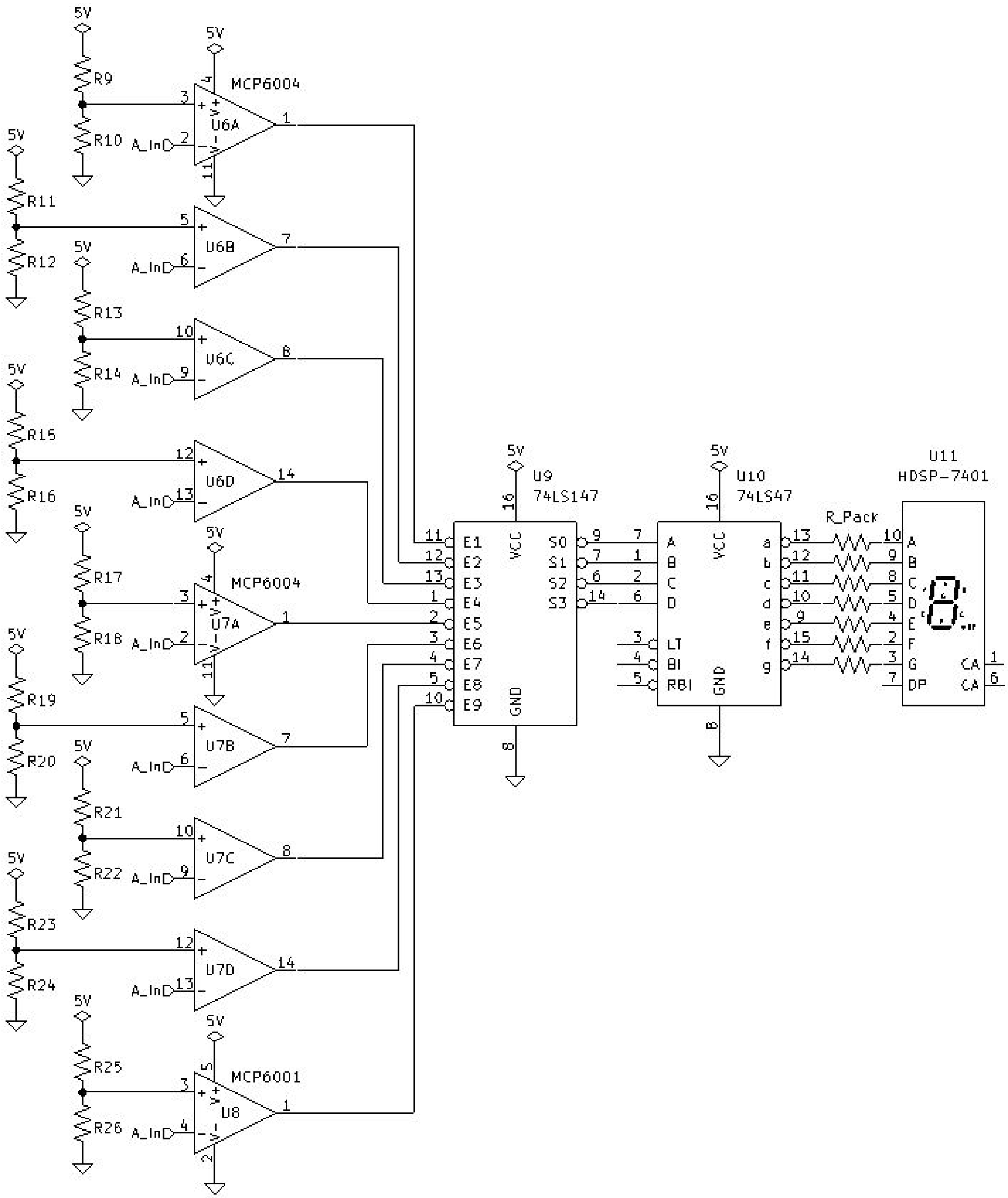


Figure 8.2: ADC Engineering Department Prototype Circuit.

8.5 Active Filtering

8.5.1 Low-Pass Active Filtering First-Order

1. See Figure 8.3 *Low-Pass First-Order Active Filtering Circuit* on page 89.
2. Calculate a Low-Pass Active Filtering First-Order circuit with a critical frequency of $20Khz$.
3. Include calculations for voltages and dB, at the following: pass-band, first octave, second octave, first decade, and the second decade.
4. Build and measure the circuit.
5. Collect data. See Table 8.2 on page 94.

8.5.2 High-Pass Active Filtering First-Order

1. See Figure 8.4 *High-Pass First-Order Active Filtering Circuit* on page 89.
2. Calculate a High-Pass Active Filtering First-Order circuit with a critical frequency between $20hz$.
3. Include calculations for voltages and dB, at the following: pass-band, first octave, second octave, first decade, and the second decade.
4. Build and measure the circuit.
5. Collect data. See Table 8.2 on page 94.

8.5.3 Band-Pass Active Filtering First-Order

1. See Figure 8.5 *Band-Pass First-Order Active Filtering Circuit* on page 90.
2. Calculate a Band-Pass Active Filtering First-Order circuit with a low critical frequency of $20hz$ and a high critical frequency of $20Khz$.
3. Make mid-band gain $\Delta V \approx -1$.
4. Include calculations for voltages and dB, at the following: mid-band, first octave, second octave, first decade, and the second decade.
5. Build and measure the circuit.
6. Collect data. See Table 8.2 on page 94.

8.5.4 Low-Pass Active Filtering Second-Order

1. See Figure 8.6 *Low-Pass Second-Order Active Filtering Circuit* on page 90.
2. Calculate a Low-Pass Active Filtering Second-Order circuit with a critical frequency of $20Khz$.
3. Include calculations for voltages and dB, at the following: pass-band, first octave, second octave, first decade, and the second decade.
4. Build and measure the circuit.
5. Collect data. See Table 8.4 on page 96.

8.5.5 High-Pass Active Filtering Second-Order

1. See Figure 8.7 *High-Pass Second-Order Active Filtering Circuit* on page 91.
2. Calculate a Low-Pass Active Filtering Second-Order circuit with a critical frequency of $20hz$.
3. Include calculations for voltages and dB, at the following: pass-band, first octave, second octave, first decade, and the second decade.
4. Build and measure the circuit.
5. Collect data. See Table 8.4 on page 96.

8.5.6 Cascaded Band-Pass Active Filtering Second-Order

1. Connect the previous two circuits in a way that will create a Cascaded Band-Pass Second-Order Active Filter circuit.
2. Include calculations for voltages and dB, at the following: mid-band, first octave, second octave, first decade, and the second decade.
3. Build and measure the circuit.
4. Collect data. See Table 8.4 on page 96.

8.5.7 Single-Stage Band-Pass Active Filtering Second-Order

1. See Figure 8.8 *Single Stage Band-Pass Second-Order Active Filtering Circuit* on page 91.
2. Calculate a Single-Stage Band-Pass Second-Order Active Filter circuit:
   (a) Resonant Frequency equals 10Khz with a Q of 1.
   (b) Resonant Frequency equals 10Khz with a Q of 10.
3. Include calculations for voltages and dB, at the following: mid-band, first octave, second octave, first decade, and the second decade.
4. Build and measure the circuit.
5. Collect data. See Table 8.4 on page 96.
6. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

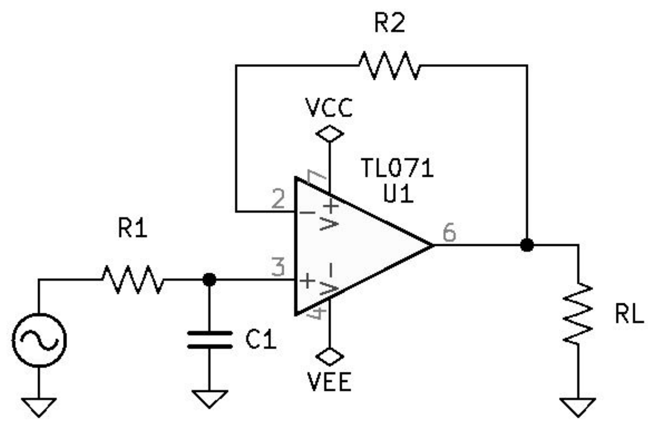


Figure 8.3: Low-Pass First-Order Active Filtering Circuit.

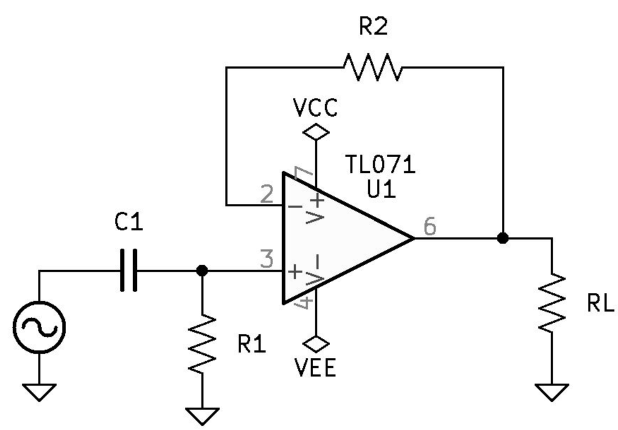


Figure 8.4: High-Pass First Order Active Filtering Circuit.

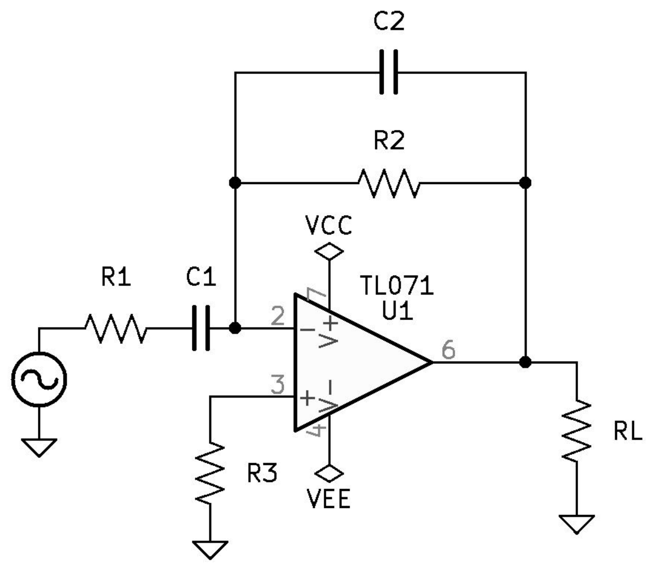


Figure 8.5: Band-Pass First-Order Active Filtering Circuit.

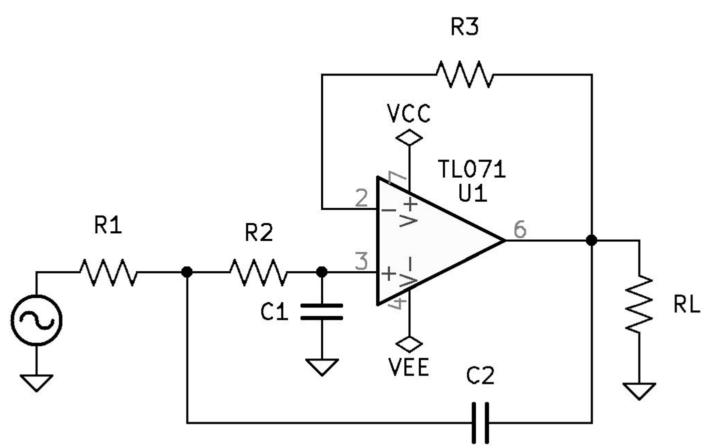


Figure 8.6: Low-Pass Second-Order Active Filtering Circuit.

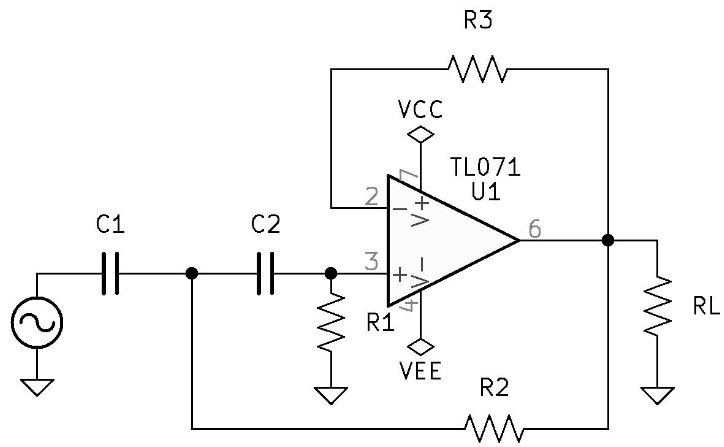


Figure 8.7: High-Pass Second-Order Active Filtering Circuit.

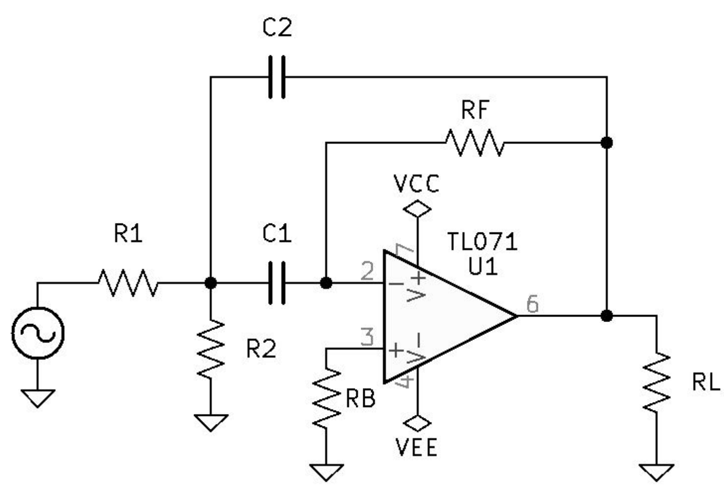


Figure 8.8: Single Stage Band-Pass Second-Order Active Filtering Circuit.

8.6 Bessel, Butterworth, & Chebyshev

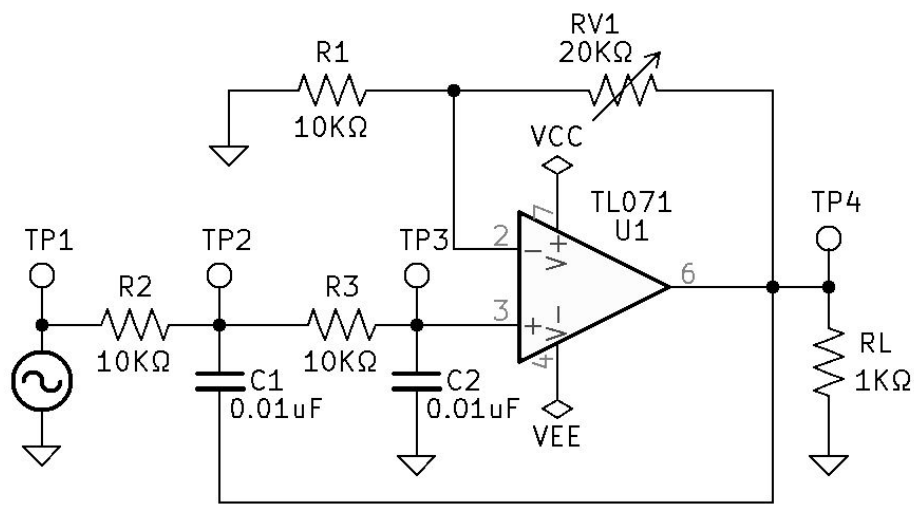


Figure 8.9: Bessel, Butterworth, Chebyshev Frequency Response Test Circuit.

Table 8.1: Bessel, Butterworth, Chebyshev Data.

Figure 8.9	$TP1$	$TP2$	$TP3$	$\frac{TP1}{TP3}$	$RV1$	$TP4$	ΔV
Bessel	$2vpp$	$1.414vpp$	$1vpp$	2	0.0Ω	$1vpp$	1
Bessel	$1.73vpp$	$1.414vpp$	$1vpp$	1.73	2.68KΩ	$1.268vpp$	1.268
Butterworth	$1.414vpp$	$1.414vpp$	$1vpp$	1.414	5.86KΩ	$1.586vpp$	1.586
Chebyshev	$1vpp$	$1.414vpp$	$1vpp$	1	10KΩ	$2vpp$	2
Chebyshev	$0.5vpp$	$1.414vpp$	$1vpp$	0.5	15KΩ	$2.5vpp$	2.5
Oscillator	$0vpp$				20KΩ	OSC.	≥ 3

8.6.1 Frequency Response Characteristics & Verification

1. See Figure 8.9 *Bessel, Butterworth, Chebyshev Frequency Response Test Circuit.*
2. See Table 8.1 *Bessel, Butterworth, Chebyshev Data.*
3. Build and measure the test circuit.
4. Verify voltages and gains for each frequency response.
5. Capture and document the frequency sweep for each response characteristic.
6. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

8.7 Collected Data

- See *Table Formatting and Data Sets Examples* on page 94.
- Include all the data sets referenced in the lab.

8.8 Key Terms

Define The Following:

- DAC
- ADC
- High Pass
- Low Pass
- Band Pass
- Octave
- Decade
- Second Octave
- Second Decade
- Active Filtering
- First-Order Filtering
- Second-Order Filtering
- Cascaded
- Bessel
- Butterworth
- Chebyshev

8.9 Key Formulas

- List and define each of the key formulas used in this lab.

8.10 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

8.11 Table Formatting and Data Sets

Table 8.2: First-Order Active Filtering (Section 8.5).

Section.8.5	Low Pass		High Pass		Band Pass	
First Order	*Calc.*	*Meas.*	*Calc.*	*Meas.*	*Calc.*	*Meas.*
FC_{LOW}			20_{HZ}		20_{HZ}	
FC_{HIGH}	$20K_{HZ}$				$20K_{HZ}$	
F_{Octave}						
F_{2_Octave}						
F_{Decade}						
F_{2_Decade}						
$Vpp_{PassBand}$						
Vpp_{FC}						
Vpp_{Octave}						
Vpp_{2_Octave}						
Vpp_{Decade}						
Vpp_{2_Decade}						
$dB_{PassBand}$						
dB_{FC}						
dB_{Octave}						
dB_{2_Octave}						
dB_{Decade}						
dB_{2_Decade}						

Table 8.3: Second-Order Active Filtering (Section 8.5).

Section.8.5	Low Pass		High Pass		Cascaded	
Second Order	*Calc.*	*Meas.*	*Calc.*	*Meas.*	*Calc.*	*Meas.*
FC_{LOW}			20_{HZ}		20_{HZ}	
FC_{HIGH}	$20K_{HZ}$				$20K_{HZ}$	
F_{Octave}						
F_{2_Octave}						
F_{Decade}						
F_{2_Decade}						
$Vpp_{PassBand}$						
Vpp_{FC}						
Vpp_{Octave}						
Vpp_{2_Octave}						
Vpp_{Decade}						
Vpp_{2_Decade}						
$dB_{PassBand}$						
dB_{FC}						
dB_{Octave}						
dB_{2_Octave}						
dB_{Decade}						
dB_{2_Decade}						

Table 8.4: Second-Order Active Filtering (Section 8.5).

Section.8.5	Single Stage 10Khz Q=1		Single Stage 10Khz Q=10	
Second Order	*Calc.*	*Meas.*	*Calc.*	*Meas.*
FC_{LOW}				
FC_{HIGH}				
$Bandwidth$				
F_{L_Octave}				
F_{H_Octave}				
F_{L_Decade}				
F_{H_Decade}				
$Vpp_{PassBand}$				
Vpp_{FC}				
Vpp_{Octave}				
Vpp_{2_Octave}				
Vpp_{Decade}				
Vpp_{2_Decade}				
$dB_{PassBand}$				
dB_{FC}				
dB_{Octave}				
dB_{2_Octave}				
dB_{Decade}				
dB_{2_Decade}				

Table 8.5: Operational Amplifiers: DAC, ADC, & Active Filtering Check-Off Sheet

<table>
<tr><td colspan="4">RCET 2252
Clinical Assistant Professor
Timothy Leishman
DAC, ADC, & Filtering Check-Off Sheet
Check-Off Sheet</td></tr>
<tr><td colspan="2">Student Name:</td><td colspan="2">Lab Start Date:</td></tr>
<tr><td>Check-Off</td><td>Section</td><td>Date</td><td>Instructor Int.</td></tr>
<tr><td>DAC Calculations</td><td>8.4.1</td><td></td><td></td></tr>
<tr><td>DAC Measurements</td><td>8.4.1</td><td></td><td></td></tr>
<tr><td>ADC Calculations</td><td>8.4.2</td><td></td><td></td></tr>
<tr><td>ADC Measurements</td><td>8.4.2</td><td></td><td></td></tr>
<tr><td>First-Order Active Filtering</td><td>8.5.1 to 8.5.3</td><td></td><td></td></tr>
<tr><td>Second-Order Active Filtering</td><td>8.5.4 to 8.5.7</td><td></td><td></td></tr>
<tr><td>Bessel, Butterworth, Chebyshev</td><td>8.6.1</td><td></td><td></td></tr>
<tr><td colspan="4">Instructor Notes:</td></tr>
<tr><td colspan="4"></td></tr>
</table>

Lab 9

Power Supply Project Part 1

Lab 10

Power Supply Project Part 2

Lab 11

Switching Transistors & Multivibrators

11.1 Objectives

Objective A: Calculate Switch Mode Transistor Voltages, Currents, and Timing Values.

1. **Voltage Calculations:** Students should be capable of calculating voltage values in switch mode transistor circuits. This involves Kirchhoff's Voltage Law and the understanding of transistor operating regions.

2. **Current Calculations:** Understand how to calculate current values within switch mode transistor circuits, taking into account transistor characteristics and circuit parameters to include the understanding of transistor saturation and overdrive.

3. **Timing Calculations:** Proficiency in determining timing values, such as pulse width, pulse space, delay time, rise time, storage time, fall time, time on, and time off.

Objective B: Calculate Astable Monostable Multivibrator Transistor Circuits.

1. **Astable Multivibrator Calculations:** Students should be able to calculate the component values, operation parameters, and waveform timing for astable multivibrator transistor circuits.

2. **Monostable Multivibrator Calculations:** Proficiency in calculating component values, operations characteristics, and waveform timing for monostable multivibrator transistor circuits.

Objective C: Calculate Astable & Monostable Multivibrator 555 Timer Circuits.

1. **Astable Multivibrator Calculations:** Students should be able to calculate the component values, operation parameters, and waveform timing for astable multivibrator 555 Timer circuits.

2. **Monostable Multivibrator Calculations:** Proficiency in calculating component values, operations characteristics, and waveform timing for monostable multivibrator 555 Timer circuits.

Objective D: Circuit Construction, Measurement and Data Collection.

1. **Measurement Skills:** Students should demonstrate the ability to use test equipment, such as oscilloscopes, DMMs, and signal generators, to accurately measure voltage, current, and timing values in switch-mode transistor circuits and multivibrator circuits.

2. **Data Collection:** Demonstrate an ability to systematically collect and record data during experimentation. Accurately document measurements, including waveforms, voltage levels, currents, timing, and other relevant parameters, ensuring organized data for analysis.

11.2 Reference Documents

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- 2N3904 Data Sheet [12]
- LM555 Data Sheet [13]
- SN7414 Data Sheet [14]
- SN74121 Data Sheet [15]
- BU4538B Data Sheet [16]

11.3 Checkoff Sheet

See Table 11.3 *Switching Transistors & Multivibrators Check-Off Sheet* on Page 109.

11.4 Switching Transistors

11.4.1 Switching Transistor Signal Characteristics

1. Draw a switching transistor characteristic waveform and identify and label the following:

   (a) delay time

   (b) rise time

   (c) turn-on time

   (d) fall time

   (e) storage time

   (f) turn-off time

11.4.2 Switching Characteristics of the 2N3904

1. Look up and document the switching transistor characteristic specifications for the 2N3904 transistor [12].

2. Build the data sheet test circuits, measure and verify the data sheet switching specifications.

11.4.3 Overdrive Switching

1. Design a switching circuit using a 2N3904 transistor with an 1KΩ collector resistor (RC).

   (a) Build and measure the switching characteristics when I_B is at saturation.

   (b) Build and measure the switching characteristics when I_B is overdriven at $2\times$ saturation.

   (c) Build and measure the switching characteristics when I_B is overdriven at $4\times$ saturation.

2. Analyze the results of over-driving the switch.

11.4.4 Commutating Capacitor & Improved Switching

1. Document the procedure for designing a transistor switching circuit that uses a Commutating Capacitor.

2. Design a switching circuit using a Commutating Capacitor and a 2N3904 transistor with an 1KΩ collector resistor (RC).

3. Build and measure the switching characteristics of the Commutating Capacitor Switching Transistor Circuit.

4. Analyze the results, noting the benefits of adding a Commutating Capacitor to a transistor switching circuit.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

11.5 Bipolar Junction Transistor Multivibrators

11.5.1 Astable Multivibrator 2N3904 Transistor

1. Include the schematic for a Bipolar Junction Transistor Astable Multivibrator circuit.
2. Provide the theory of operation for the Bipolar Junction Transistor Astable Multivibrator Circuit.
3. Design an Astable Multivibrator using 2N3904 transistors to provide a 50% duty cycle and an Instructor-assigned PRF. (ask your instructor for an assigned frequency)
4. Build and measure the designed circuit.
5. Document the measured waveform, frequency, voltage levels, Pulse Width, Pulse Space, Rise Time, and Fall Time.

11.5.2 Astable Multivibrator Improved Rise Time

1. Include the schematic for a Bipolar Junction Transistor Astable Multivibrator with an Improved Rise Time circuit.
2. Provide the theory of operation for the Improved Rise Time Circuit.
3. Build and measure the Improved Rise Time Circuit for the previously designed Astable Multivibrator.
4. Document the measured waveform, frequency, voltage levels, Pulse Width, Pulse Space, Rise Time, and Fall Time.
5. Analyze and compare the measured results of the Improved Rise Time Circuit.
6. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

11.5.3 Monostable Multivibrator 2N3904

1. Include the schematic for a Bipolar Junction Transistor Monostable Multivibrator circuit.
2. Provide the theory of operation for the Bipolar Junction Transistor Monostable Multivibrator Circuit.

3. Design a Monostable Multivibrator using 2N3904 transistors to provide an output pulse equivalent to a 10% duty cycle of the previously Instructor-assigned PRF.

4. Build and measure the designed circuit.

11.5.4 Extreme Duty Cycle Astable Multivibrator

1. Create a schematic that connects the Astable circuit from Section 11.5.2 to the Monostable circuit from Section 11.5.3. The output of the Astable circuit must be differentiated enough to avoid any interference with the short pulse width of the Monostable.

2. Provide a theory of operation for the Extreme Duty Cycle Circuit.

3. Build and measure the Extreme Duty Cycle Circuit.

4. Document the measured waveforms, frequency, voltage levels, Pulse Width, Pulse Space, and Duty Cycle.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

11.6 Schmitt Trigger Inverter Astable Multivbrator

1. Review the SN7414 Schmitt Trigger Inverter Data Sheet [14].

2. Include a schematic for a Schmitt Trigger Inverter Astable Multivibrator.

3. Provide a theory of operation for the Schmitt Trigger Inverter Astable Multivibrator.

4. Show the procedure for calculating the Schmitt Trigger Inverter Astable Multivibrator.

5. Design a Schmitt Trigger Inverter Astable Multivibrator that will produce a 5hz output.

6. Repeat the previous step for a 50Khz output.

7. Build and measure the calculated Schmitt Trigger Inverter Astable Multivibrator circuits.

8. Document the measured waveforms.

9. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

(b) Be prepared to answer questions and demonstrate measurements made in this section.

11.7 555 Timer Multivibrators

11.7.1 Astable Multivibrator 555 Timer

1. Review the LM555 Timer Data Sheet [13].

2. Design a 555 Timer Astable Multivibrator with a 70% Duty Cycle and the PRF previously assigned in Section 11.5.1.

3. Calculate and draw the capacitor voltage waveform in reference to the output voltage waveform.

4. Build and measure the 555 Astable Multivibrator circuit.

5. Document the measured waveforms.

11.7.2 Monostable Multivibrator 555 Timer

1. Design a 555 Timer Monostable Multivibrator to produce a $5\mu s$ output pulse when triggered.

2. Construct the Astable Multivibrator previously designed in Section 11.7.1 to trigger the 555 Timer Monostable Multivibrator.

3. Provide the theory of operation for the circuit.

4. Build and measure the designed circuit.

5. Document the measured waveforms.

6. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

11.8 Monostable Multivibrators Integrated Circuits

11.8.1 SN74121 & BU4538B

1. Review the data sheet for the SN74121 [15] and note key features and specifications.

2. Review the data sheet for the BU4538B [16] and note key features and specifications.

3. Design and assemble a Monostable Multivibrator using either the SN74121 IC or the BU4538B IC to produce a 5μs pulse.

4. Design and assemble a Monostable Multivibrator using either the SN74121 IC or the BU4538B IC to produce a 5s pulse.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

11.9 Collected Data

- See *Table Formatting and Data Sets Examples* on page 107.
- Include all the data sets referenced in the lab.

11.10 Key Terms

Define The Following:

- delay time
- rise time
- turn-on time
- storage time
- fall time
- turn-off time
- multivibrator
- astable
- bistable
- monostable
- duty cycle
- SN7414
- 555 timer
- SN74121
- BU4538B

11.11 Key Formulas

- List and define each of the key formulas used in this lab.

11.12 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.

2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

11.13 Table Formatting and Data Sets

Table 11.1: Switching Transistors (Section 11.4).

Section.11.4.2	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
Specification						
Measured						
Section.11.4.3	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
$Saturation_{Meas.}$						
2xOD$_{Meas.}$						
4xOD$_{Meas.}$						
Section.11.4.4	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
$Measured_{ComCap}$						

Table 11.2: 2N3904 Astable Multivibrators Data (Section 11.5).

Section.11.5.1	PRF	PW	PS	DC	t_{rise}	t_{fall}	V_{OH}	V_{OL}
Calculated								
Measured								
Section.11.5.2	PRF	PW	PS	DC	t_{rise}	t_{fall}	V_{OH}	V_{OL}
Measured								
Section.11.5.4	PRF	PW	PS	DC	t_{rise}	t_{fall}	V_{OH}	V_{OL}
Calculated								
Measured								

Table 11.3: Switching Transistors & Multivibrators Check-Off Sheet

<table>
<tr><td colspan="4" align="center">RCET 2252
Clinical Assistant Professor
Timothy Leishman
Switching Transistors & Multivibrators
Check-Off Sheet</td></tr>
<tr><td colspan="2">Student Name:</td><td colspan="2">Lab Start Date:</td></tr>
<tr><td>Check-Off</td><td>Section</td><td>Date</td><td>Instructor Int.</td></tr>
<tr><td>Switching Transistors</td><td>11.4</td><td></td><td></td></tr>
<tr><td>Bipolar Junction Transistor Astable Improved</td><td>11.5</td><td></td><td></td></tr>
<tr><td>Bipolar Junction Transistor Astable Extreme DC</td><td>11.5</td><td></td><td></td></tr>
<tr><td>Schmitt Trigger Inverter Astable Multivbrator</td><td>11.6</td><td></td><td></td></tr>
<tr><td>555 Timer Multivibrators</td><td>11.7</td><td></td><td></td></tr>
<tr><td>Monostable Multivibrators Integrated Circuits</td><td>11.8</td><td></td><td></td></tr>
<tr><td colspan="4" align="center">Instructor Notes:</td></tr>
<tr><td colspan="4"></td></tr>
</table>

Lab 12

Linear Regulators & Switching Power Supplies

12.1 Objectives

Objective A: Document the Characteristics of a Linear Regulator.

1. **Linear Regulator Characteristics:** Students should be able to document key characteristics and specifications of linear regulator integrated circuits.

Objective B: Use a Linear Regulator to regulate Voltage & Current.

1. **Voltage Regulation:** Proficiency in using a linear regulator to regulate and control output voltage within specified limits despite variations in input voltage and load.

2. **Current Regulation:** Proficiency in using a linear regulator to regulate and control output current within specified limits.

Objective C: Calculate & Measure Heat-Sink Power Dissipation Capabilities.

1. **Heat-Sink Calculations:** Students should be capable of calculating the required heat-sink power dissipation capabilities.

2. **Measurement:** Demonstrate the ability to measure and verify heat-sink power dissipation capabilities by taking advantage of the internal temperature protection circuit of the LM317 Linear Regulator.

Objective D: Document Types & Characteristics of Switch Mode Power Supplies (SMPS).

1. **Documentation:** Document the various types and characteristics of Switch Mode Power Supplies (SMPS), including topology, efficiency, voltage regulation, and switching frequency.

Objective E: Design a Switch Mode Power Supply (SMPS).

1. **SMPS Design:** Develop the skills to design a Switch Mode Power Supply, considering factors such as voltage requirements, load characteristics, and efficiency goals.

Objective F: Develop a SMPS Troubleshooting Procedure/Checklist.

1. **Troubleshooting Procedure:** Create a structured procedure or checklist for diagnosing and addressing common issues in a Switch Mode Power Supply (SMPS) system.

Objective G: Explain the Advantages and Disadvantages of SMPS over Linear Regulated Power Supplies.

1. **Advantages and Disadvantages:** Students should be able to articulate the advantages and disadvantages of using Switch Mode Power Supplies (SMPS) in comparison to Linear Regulated Power Supplies. This includes aspects such as efficiency, size, and noise.

12.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books
- LM317 Datasheet [17]
- Heatsink HSE-20635H-W Datasheet [18]
- BS170 Datasheet [19]
- IRF9Z24N Datasheet [20]
- TL494 Datasheet [21]
- Texas Instruments Designing Switching Voltage Regulators with the TL494 [22]
- MC34063ACN Datasheet [23]

12.3 Checkoff Sheet:

See Table 12.3 *Linear Regulators & SMPS Check-Off Sheet* on Page 121.

12.4 LM317 Linear Regulators

12.4.1 LM317 Specifications and Features

1. Review the LM317 linear regulator data sheet [17] and document important specifications & features.

12.4.2 Fixed Voltage Regulation

1. Design a fixed voltage regulator using the LM317 to provide 25VDC output with a 40VDC input voltage.

2. Provide a schematic and all calculations.
3. Build, measure, and verify the following:
   (a) Verify voltage regulation by measuring the regulated output voltage across a range of load resistances.
   (b) Set the load resistance to 1KΩ and verify voltage regulation throughout a range of input voltages by lowering the 40VDC. Find the minimum input voltage that will maintain the fixed output.

   Section Check-Off:
4. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.4.3 Variable Voltage Regulation

1. Design a variable voltage regulator using the LM317 to provide a 5VDC to 25VDC output with a 40VDC input voltage.
2. Provide a schematic and all calculations.
3. Build, measure, and verify the voltage range.
4. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.4.4 Fixed Current Regulation

1. Design a circuit using the LM317 to provide a fixed current limiting of 0.5 amps.
2. Provide a schematic and all calculations.
3. Build, measure, and verify fixed current limiting.
4. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.4.5 Variable Current Regulation

1. Design a circuit using the LM317 to provide variable current limiting with a range of 0.2 amps to 1.0 amps.
2. Provide a schematic and all calculations.
3. Build, measure, and verify variable current limiting.
4. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.4.6 LM317 Variable Current & Variable Voltage Circuit.

1. Using LM317s, design a circuit that provides a variable current of 0.2 amps to 1.0 amp & a variable voltage of 5VDC to 25VDC.
2. Show schematic with resistor values. Do not build.

12.5 Heat Sink Calculation Verification

1. Calculate the max power dissipation of the HSE20635-035H-W heat sink.
2. Taking advantage of the LM317 internal thermal protection circuitry, design a circuit that will exceed the calculated max power dissipation of the HSE20635-035H-W heat sink.
3. Build and measure circuit noting the actual power dissipation of the HSE20635-035H-W heat sink.
4. Clearly document your calculations, testing procedure, and steps for measuring the heat sink's maximum power dissipation.

   Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.6 Unregulated Discrete Switch Mode Power Supply BUCK Design

12.6.1 The Switch

1. Review the data sheets for the BS170 [19] and the IRF9Z24N [20].
2. Design a circuit to test the switching ability of the BS170. See *Switch Test Circuit 1* Figure 12.1. Make $VCC = 40V$.
3. Verify that the BS170 is functioning as a switch.
4. Design a circuit to test the switching ability of the IRF9Z24N. See *Switch Test Circuit 2* Figure 12.2. Make $VCC = 40V$.
   - Note: V_{th} is the minimum voltage to turn on the transistor. V_{thMAX} is not the maximum gate to source voltage, it is the voltage that will turn on 100% of the manufactured MOSFETS. Point of Discovery: RDS_{on} does change with respect to VGS, more VGS will equal a lower RDS_{on} making the FET a better switch. However, do not exceed VGS_{max}.
5. Verify that the IRF9Z24N is functioning as a switch.

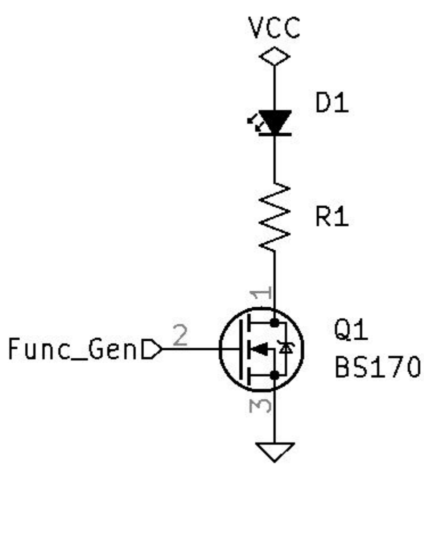


Figure 12.1: Switch Test Circuit 1

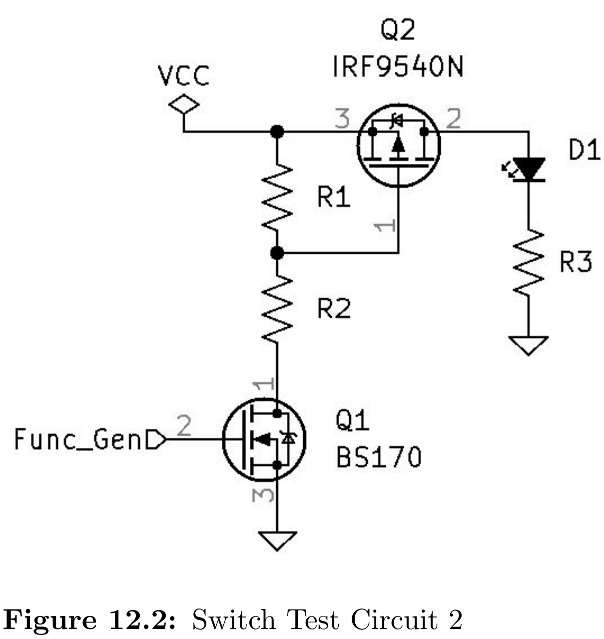


Figure 12.2: Switch Test Circuit 2

12.6.2 Inductor & Capacitor Calculations

1. See *SMPS BUCK Discrete Circuit* Figure 12.3.

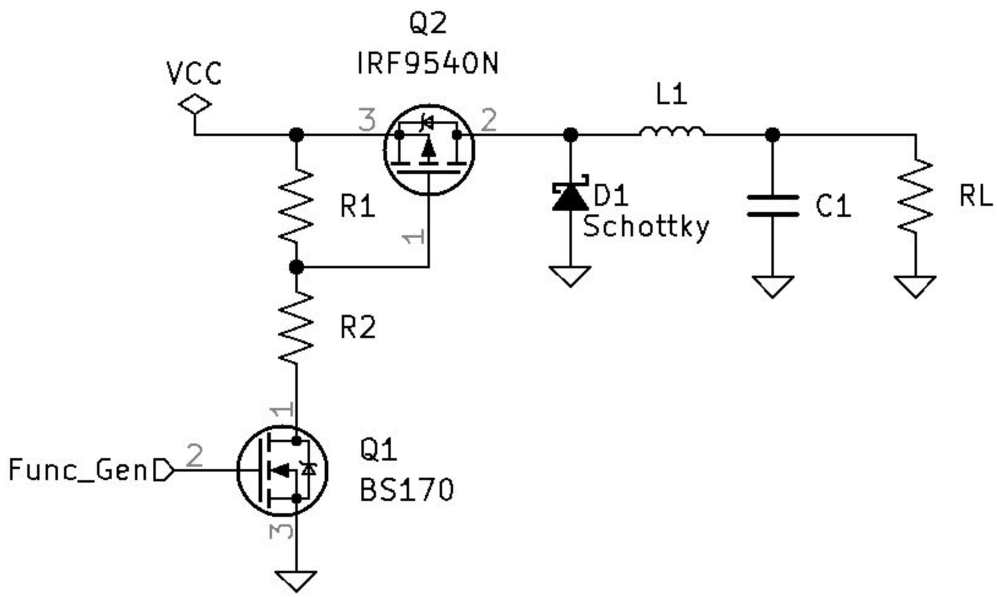


Figure 12.3: SMPS BUCK Discrete Circuit

2. Make VCC equal to 40V & IRL_{MAX} equal to 1 amp.
3. Show all calculations for L1.
4. Show all calculations for C1.

12.6.3 PWM Duty Cycle & Load Testing

1. Test the circuit by adjusting the duty cycle of the function generator. Record duty cycle data for C1 = $22\mu F$ and RL=$10K\Omega$, $1K\Omega$, and 100Ω, see Table 12.1.
2. Minimize output ripple voltage by optimizing C1 for the circuit, see Table 12.2.

   Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.7 Regulated Discrete Switch Mode Power Supply BUCK Design

1. Review the TL494 Data Sheet [21].
2. Document key features and specifications of the TL494. ??.
3. Review Figure 10-1 of *Texas Instruments TL494 Data Sheet* [21] and Figure 35 of *Designing Switching Voltage Regulators with the TL494* [22]

See Figure 8-1

PARAMETER	TEST CONDITIONS	MIN	TYP(1)	MAX	UNIT
Input threshold voltage (FEEDBACK)	Zero duty cyle		4	4.5	V
Input sink current (FEEDBACK)	V (FEEDBACK) = 0.7 V	0.3	0.7		mA

Figure 12.4: TL494 Data Sheet Excerpt

- **WARNING!** The feedback input maximum voltage is 4.5V. If the Feedback voltage input threshold exceeds 4.5V the part will be destroyed.

4. Build and test the 5V regulation circuit with the following substitutions:
   - Use the previously designed Switching Circuit Figure 12.3 instead of the BJT switches.
   - Adjust the current limiting to 0.5 amps.
5. Verify the circuit's ability to maintain regulation by testing the 5v output with a variety of load currents.
6. Modify the circuit to achieve variable voltage with a minimum of 5v to 25v regulated output.
7. Test the power supply's ability to regulate across a wide range of voltages and loads.
8. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.8 SMPS IC MC34063ACN

12.8.1 MC34063ACN Buck

1. Review the Data Sheet and document key specifications and features pertaining to the use and configuration of the MC34063 as a Buck SMPS.

Table 3. Absolute maximum ratings

Symbol	Parameter		Value	Unit
V_{CC}	Power supply voltage		50	V
V_{IR}	Comparator input voltage range		-0.3 to 40	V
V_{SWC}	Switch collector voltage		40	V
V_{SWE}	Switch emitter voltage (V_{SWC} = 40V)		40	V
V_{CE}	Switch collector to emitter voltage		40	V
V_{DC}	Driver collector voltage		40	V
I_{DC}	Driver collector current		100	mA
I_{SW}	Switch current		1.5	A
P_{TOT}	Power dissipation at T_A = 25°C	for DIP-8	1.25	W
		for SO-8	0.625	
T_J	Operating junction temperature		150	°C
T_{STG}	Storage temperature range		-40 to 150	°C
T_{OP}	Operating ambient temperature range	for AC and EC series	0 to 70	°C
		for AB series	-40 to 85	
		for EB series	-40 to 125	

Figure 12.5: MC34063 Maximum Specifications Data Sheet Excerpt

2. Notice that the maximum power dissipation is 1.25W for the DIP-8 package.

3. Design a BUCK SMPS using the MC34063 to accept 30VDC on the input and provide an output of 15VDC.

   - Caution! Make sure to not exceed the power limitations of the IC.
   - If the Buck configuration is ≈ 80% efficient, and max power of the DIP-8 is ≈ $1w$. Calculate maximum output power.

     $\frac{P_{out}}{P_{total}} = 80\%,\ P_{total} = P_{MC34063} + P_{out} = 1W + P_{out}$

     $\frac{P_{out}}{1W+P_{out}} = 80\%$

     $P_{out} = (1W + P_{out}) \times 0.8$

     $P_{out} = 0.8W + 0.8P_{out}$

     $P_{out} - 0.8P_{out} = 0.8W$

     $0.2P_{out} = 0.8W$

     $P_{out} = \frac{0.8W}{0.2} = 4W$

     $P_{outMAX} = 4W$

   - Keep the output power ≤ 4 watts when using the standard Buck circuit. If more power is needed, use the high-power circuit variation noted in the data sheet.

12.8.2 MC34063ACN Boost

1. Review the Data Sheet and document key specifications and features pertaining to the use and configuration of the MC34063 as a BOOST SMPS.

2. Design a Boost SMPS using the MC34063 to accept 5VDC on the input and provide an output of 10VDC.

12.8.3 MC34063ACN Inverter

1. Review the Data Sheet and document key specifications and features pertaining to the use and configuration of the MC34063 as an Inverting SMPS.

2. Design an Inverting SMPS using the MC34063 to accept 5VDC on the input and provide an output of -10VDC.

3. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

12.9 Collected Data

- See *Table Formatting and Data Sets Examples* on page 120.
- Include all the data sets referenced in the lab.

12.10 Key Terms

Define The Following:

- Linear Power Supply
  - Advantages
  - Disadvantages
- SMPS
  - Advantages
  - Disadvantages
- Unregulated
- Regulation
- PWM
- Buck
- Boost
- Inverter
- TL494
- MC34063ACN

12.11 Key Formulas

- List and define each of the key formulas used in this lab.

12.12 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

12.13 Table Formatting and Data Sets

Table 12.1: Duty Cycle Testing (Section 12.6.3).

RL=10$K\Omega$, C1=22μF	10%DC	20%DC	30%DC	40%DC	50%DC	Vpp_{Ripple}
Measured V_{OUT}						
RL=1$K\Omega$, C1=22μF	10%DC	20%DC	30%DC	40%DC	50%DC	Vpp_{Ripple}
Measured V_{OUT}						
RL=100Ω, C1=22μF	10%DC	20%DC	30%DC	40%DC	50%DC	Vpp_{Ripple}
Measured V_{OUT}						

Table 12.2: Load Testing (Section 12.6.3).

RL=25Ω, C1=22μF	DutyCycle	Vpp_{Ripple}	%Ripple
V_{OUT}=25V_{DC}			
RL=25Ω, C1=220μF	DutyCycle	Vpp_{Ripple}	%Ripple
V_{OUT}=25V_{DC}			
RL=25Ω, C1=470μF	DutyCycle	Vpp_{Ripple}	%Ripple
V_{OUT}=25V_{DC}			

Table 12.3: Linear Regulators & SMPS Check-Off Sheet

RCET 2252
Clinical Assistant Professor
Timothy Leishman

Linear Regulators & SMPS
Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
Linear Regulation Fixed Voltage	12.4.2		
Linear Regulation Variable Voltage	12.4.3		
Linear Regulation Fixed Current	12.4.4		
Linear Regulation Variable Current	12.4.5		
Heat Sink Verification	12.5		
Unregulated Discrete SMPS	12.6.3		
Regulated Discrete SMPS	12.7		
MC34063 Buck	12.8.1		
MC34063 Boost	12.8.2		
MC34063 Inverter	12.8.3		

Instructor Notes:

Lab 13

DC Motors, Solenoids, and Servos

13.1 Objectives

Objective A: Document the Characteristics of DC Motors, Solenoids, & Servo Motors.

1. **DC Motors Documentation:** Students should be able to document key characteristics of DC motors, including specifications such as voltage ratings, current requirements, torque-speed characteristics, and efficiency.

2. **Solenoids Documentation:** Proficiency in documenting characteristics of solenoids, encompassing details like voltage requirements, force exerted, response time, and applications.

3. **Servo Motors Documentation:** Understand and document characteristics of servo motors, including parameters such as resolution, torque, speed, and control mechanisms.

13.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books

13.3 Checkoff Sheet:

See Table 13.3 *DC Motors, Solenoids, and Servos Check-Off Sheet* on Page 130.

13.4 Lab Instructions:

13.5 DC Motors (Brushed)

13.5.1 DC Brushed Motor theory of operation

1. Describe the operation of the DC Brushed Motor and identify major components and functions.

13.5.2 DC Motor Verification & Initial Testing

Verify DC Motor Operation Steps:

1. DC Voltage
2. Required Current
3. RPM
4. Document measured values. See Table 13.1 DC Motor Verification & Initial Testing (Section 13.5.2).
5. Repeat the previous steps while decreasing VDC by 10% for each iteration.

13.5.3 Switch Operation and PWM Speed Control

1. Design and test an N-Channel FET switching circuit to turn on & off the DC motor.
2. Design and test a P-Channel FET switching circuit to turn on & off the DC motor.
3. Connect both circuits together in series with the motor in between.
4. Enable (turn on) one of the FETs and use a Function Generator set to $16K_{HZ}$ to provide a PWM signal to pulse width modulate the other FET.
5. Document measured values. See Table 13.2 Switch Operation and PWM Speed Control (Section 13.5.3).

13.5.4 H-Bridge Direction Control

1. Design an H-Bridge to provide direction control for the motor.
2. Verify that the motor can operate in both the clockwise and counterclockwise motion.
3. Verify that speed control is working using PWM from the function generator.

13.5.5 TL494 Analog Voltage Controlled PWM

1. Using a TL494 design a circuit to replace the 16K$_{HZ}$ PWM signal from the Function Generator.

2. Verify circuit speed control using the TL494.

3. Consider the Analog Out resolution of Labview and the QY@ board and compare the theoretical resolution to the resolution of the Second Semester PWM speed control circuit.

13.5.6 Logic Control Circuitry

1. Add direction control logic that will prevent H-Bridge shoot-through and allow change of direction using a single input signal. Include direction LED indicators.

2. Add protection circuit logic that prevents the motor from changing direction while it is in motion (will only change direction when the speed is at zero).

3. Add a motor logic kill switch for the remote operator.

4. Add a motor mechanical kill switch for the local operator.

13.5.7 RPM Monitoring Circuitry

1. Design an LED circuit with a TTL output, to monitor the motor RPMs.

2. Verify RPM signal operation and accuracy using the Oscilloscope and Tachometer.

3. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

13.6 Solenoid

13.6.1 Solenoid Theory of Operation

1. Describe the operation of the Solenoid and identify major components and functions.

13.6.2 Solenoid Verification and Control Circuit

1. Caution:(Some solenoids, if energized for too long, will be damaged) The car door lock solenoids we use in this lab experiment will be destroyed if energized for too long.

2. Briefly, $\approx 1 second$, energize the solenoid and measure the drive current.

3. Design a Monostable Multivibrator using the SN74121 to provide a one-second solenoid trigger signal.

4. Design a circuit that will allow the solenoid to push and pull (direction control). Limit the energize time to one second and provide direction and active energize indication.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

13.7 Servo

13.7.1 Servo Theory of Operation

1. Describe the operation of the Servo and identify major components and functions.

13.7.2 Servo Verification and Control Circuit

1. Using the Function Generator, verify servo operation and the servo PWM signal.

2. Design a circuit using a variable resistor and a 555 timer to replace the function generator. Build and test the circuit.

3. Modify the circuit by replacing the variable resistor with two parallel fixed resistors in series with a single pole double throw switch to provide a switchable two-position servo control signal at 25% and 75% positions.

4. Modify the circuit by replacing the mechanical switch with two Enhanced P-Channel MOSFETs that can be switched, from opposite states, from a single TTL logic signal. For example, a logic High will provide servo position one, and a logic Low will provide servo position two.

5. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

(b) Be prepared to answer questions and demonstrate measurements made in this section.

13.8 Electronic Speed Control (ESC)

13.8.1 ESC Brushed DC Motor

1. Describe the operation of the ESC for a Brushed DC Motor and identify major components and functions.
2. Develop a schematic and procedure for testing the ESC.
3. Bench test the ESC.
4. Document PWM control signals vs. RPM and Direction.
5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

13.8.2 ESC Brushless DC Motor

1. Describe the operation of the ESC for a Brushed DC Motor and identify major components and functions.
2. Develop a schematic and procedure for testing the ESC.
3. Bench test the ESC.
4. Document PWM control signals vs. RPM and Direction.
5. Section Check-Off:
   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.
   (b) Be prepared to answer questions and demonstrate measurements made in this section.

13.9 Collected Data

- See *Table Formatting and Data Sets Examples* on page 127.
- Include all the data sets referenced in the lab.

13.10 Key Terms

Define The Following:

- DC Motor
- Bushed vs. Brushless motors
- H-Bridge
- PWM
- Solenoid
- Servo
- Servo PWM
- RPM
- ESC

13.11 Key Formulas

- List and define each of the key formulas used in this lab.

13.12 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

13.13 Table Formatting and Data Sets

Table 13.1: DC Motor Verification & Initial Testing (Section 13.5.2).

Section.13.5.2	*VDC*	*Current*	*RPM*
100%			
90%			
80%			
70%			
60%			
50%			
40%			
30%			
20%			
10%			

Table 13.2: Switch Operation and PWM Speed Control (Section 13.5.3).

Section.13.5.3	$Frequency$	$Time_{ON}$	$Current$	RPM
99% Duty Cycle				
90% Duty Cycle				
80% Duty Cycle				
70% Duty Cycle				
60% Duty Cycle				
50% Duty Cycle				
40% Duty Cycle				
30% Duty Cycle				
20% Duty Cycle				
10% Duty Cycle				

Table 13.3: DC Motors, Solenoids, and Servos Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

DC Motors, Solenoids, and Servos

Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
DC Motor	13.5.7		
Solenoid	13.6.2		
Servo	13.7.2		
ESC Brushed DC Motor	13.8.1		
ESC Brushless DC Motor	13.8.2		

Instructor Notes:

Lab 14

Stepper Motors

14.1 Objectives

Objective A: Stepper Motor Documentation.

1. Document the Characteristics and Applications of Stepper Motors.
2. Document various applications of stepper motors in different industries and scenarios, showcasing their versatility and advantages.

Objective B: Develop Motor Control Circuits and Test Verification Procedures.

1. Motor Control Circuit Development: Students should be able to design, build, and document motor control circuits suitable for driving stepper motors. This involves selecting appropriate components, determining control signals, and implementing circuitry for precise motor control.
2. Test Verification Procedures: Develop comprehensive testing procedures to verify the functionality and performance of the motor control circuits. This includes testing aspects such as step accuracy, speed, and direction control.
3. Practical Implementation: Demonstrate the practical implementation of the developed motor control circuits and test verification procedures. Ensure the successful operation of the stepper motor under different conditions, validating the effectiveness of the designed circuits and testing protocols.

14.2 Reference Documents:

- Theory Notes
- First Year Text Books
- First Year Laboratory Books

- 74194 Shift Register datasheet [24]
- JK Flip Flop datasheet [25]
- Stepper Motor 17HS13-0316S Stepper Motor [26]
- Pololu A4988 Stepper Driver [27]
- TMC2208 datasheet [28]

14.3 Checkoff Sheet:

See Table 14.3 *Stepper Motors Check-Off Sheet* on Page 138.

14.4 Stepper Motor Control Circuitry

14.4.1 Stepper Motor General Operation and Specifications

1. Describe the general operation of a Stepper Motor and identify major components and functions.
2. Review the datasheet for your assigned stepper uni-polar motor and document key features and specifications.
3. **8V stepper motor drive voltage**. For initial testing purposes, design your circuits using a drive voltage well below the maximum rated voltage of the stepper motor.

14.4.2 Universal Shift Register SN74194 whole-step

1. Review the data sheet for the Universal Shift Register SN74194 and document key features and specifications [24].
2. Design a stepper motor control circuit using the SN74194 that will drive the stepper motor and allow for direction control (CW/CCW) while being clocked by a function generator.
3. Measure the degrees of rotation per step:
   (a) Set your function generator to a low frequency ≈20Hz.
   (b) Use a stopwatch to time one revolution on the stepper motor dial. Do this a few times and find the average time.
   (c) One revolution is equal to 360°.
   (d) Convert time to the number of cycles, clocks, and steps.
   (e) Solve for degrees per step by dividing 360° by the total number of steps.

4. Measure the maximum clock frequency at which the stepper motor maintains stable operation.

5. Calculate and document a range of RPM (Revolutions Per Minute) vs. clock frequency.

6. Measure the previously calculated RPM vs clock frequency using the tachometer or stopwatch.

7. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

14.4.3 JK Flip Flops whole-step

1. Review the data sheet for the JK Flip Flop and document key features and specifications [25].

2. Design a stepper motor control circuit using a whole step 4-bit JK Flip Flop Ring Counter that will drive the stepper motor and allow for direction control (CW/CCW) while being clocked by a function generator.

3. Measure the degrees of rotation per step (instructions previously noted in section 14.4.2.

4. Measure the maximum clock frequency at which the stepper motor maintains stable operation.

5. Calculate and document a range of RPM (Revolutions Per Minute) vs. clock frequency.

6. Measure the previously calculated RPM vs clock frequency using the tachometer or stopwatch.

14.4.4 JK Flip Flops half-step

1. Design a stepper motor control circuit using a half step 4-bit JK Flip Flop Ring Counter that will drive the stepper motor and allow for direction control (CW/CCW) while being clocked by a function generator.

2. Measure the degrees of rotation per step (instructions previously noted in section 14.4.2.

3. Measure the maximum clock frequency at which the stepper motor maintains stable operation.

4. Calculate and document a range of RPM (Revolutions Per Minute) vs. clock frequency.

5. Measure the previously calculated RPM vs clock frequency using the tachometer or stopwatch.

6. Section Check-Off:

   (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

14.4.5 A4988 Stepper Motor Driver

1. Verify the current limiting is set below the maximum coil current for the stepper motor.

2. Design a stepper motor control circuit using an A4988 Stepper Motor Driver that will drive the stepper motor at full, 1/2, 1/4, 1/8, and 1/16 steps and allow for direction control (CW/CCW) while being clocked by a function generator.

3. For each step configuration, measure the following:

   (a) Measure the degrees of rotation per step (instructions previously noted in section 14.4.2.

   (b) Measure the maximum clock frequency at which the stepper motor maintains stable operation.

   (c) Calculate and document a range of RPM (Revolutions Per Minute) vs. clock frequency.

   (d) Measure the previously calculated RPM vs clock frequency using the tachometer or stopwatch.

   Section Check-Off:

4. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

14.4.6 TMC2208 Stepper Motor Driver

1. Verify the current limiting is set below the maximum coil current for the stepper motor.

2. Design a stepper motor control circuit using an A4988 Stepper Motor Driver that will drive the stepper motor at 1/2, 1/4, 1/8, and 1/16 steps and allow for direction control (CW/CCW) while being clocked by a function generator.

3. For each step configuration, measure the following:

(a) Measure the degrees of rotation per step (instructions previously noted in section 14.4.2.

(b) Measure the maximum clock frequency at which the stepper motor maintains stable operation.

(c) Calculate and document a range of RPM (Revolutions Per Minute) vs. clock frequency.

(d) Measure the previously calculated RPM vs clock frequency using the tachometer or stopwatch.

Section Check-Off:

4. (a) Prior to Instructor check-off, make sure all of the section steps are completed and your lab book is up to date.

   (b) Be prepared to answer questions and demonstrate measurements made in this section.

14.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 107.
- Include all the data sets referenced in the lab.

14.6 Key Terms

Define The Following:

- Stepper Motor
- Resolution
- Degrees per Step
- Ring Counter
- Universal Shift Register
- A4988 Stepper Driver
- TMC2208

14.7 Key Formulas

- List and define each of the key formulas used in this lab.

14.8 Stepper Motor Trouble Shooting Procedure

1. Develop a step-by-step procedure for troubleshooting and testing a stepper motor and stepper motor control and drive circuitry.

14.9 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

14.10 Table Formatting and Data Sets

Table 14.1: Stepper Motor Circuit Degrees per Step Data

Degree/Step	1Step	$\frac{1}{2}$Step	$\frac{1}{4}$Step	$\frac{1}{8}$Step	$\frac{1}{16}$Step
SN74194 Predicted					
SN74194 Measured					
JK FF Predicted					
JK FF Measured					
A4988 Predicted					
A4988 Measured					
TMC2208 Predicted					
TMC2208 Measured					

Table 14.2: Stepper Motor Circuit measured RPM and Clock Frequency

RPM/Freq	Max RPM	Max Freq
SN74194 1Step		
JK FF 1Step		
JK FF $\frac{1}{2}$Step		
A4988 1Step		
A4988 $\frac{1}{2}$Step		
A4988 $\frac{1}{4}$Step		
A4988 $\frac{1}{8}$Step		
A4988 $\frac{1}{16}$Step		
TMC2208 $\frac{1}{2}$Step		
TMC2208 $\frac{1}{4}$Step		
TMC2208 $\frac{1}{8}$Step		
TMC2208 $\frac{1}{16}$Step		

Table 14.3: Stepper Motors Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

Stepper Motors

Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
Universal Shift Register with Direction Control	14.4.2		
JK Flip Flop Whole Step with Direction Control	14.4.3		
JK Flip Flop Half Step with Direction Control	14.4.4		
A4988 Stepper Motor Driver	14.4.5		
TMC2208 Stepper Motor Driver	14.4.6		
Instructor Notes:			

Lab 15

LabVIEW Integration

15.1 Objectives

Objective A: Document the Characteristics and Applications of LabVIEW Systems Integration.

1. Characteristics Documentation: Students should be able to document key characteristics of LabVIEW systems integration, including features, capabilities, and potential applications in various industries.

2. Applications Documentation: Understand and document diverse applications of LabVIEW systems integration, showcasing its versatility and advantages in different scenarios.

Objective B: Use LabVIEW to Create a Graphical User Interface (GUI)and Program to provide Computer Control of the DC Motor, Servo, Solenoid, and Stepper Motor Control Circuits in the Previous Labs.

1. GUI Development: Proficiency in using LabVIEW to design and create a Graphical User Interface (GUI) that is user-friendly and effective for controlling motor control circuits.

2. Program Creation: Develop a LabVIEW program that enables computer control of motor control circuits, integrating features for precise control, monitoring, and data logging.

Objective C: Troubleshooting Procedure.

1. **Troubleshooting Development:** Students should be able to create a systematic troubleshooting procedure for LabVIEW-integrated motor control circuits. This includes identifying common issues, providing step-by-step diagnostics, and suggesting resolutions.

15.2 Reference Documents:

- Theory Notes
- LabVIEW Notes
- DC Motors, Solenoids, and Servo Lab Documentation
- Stepper Motor Lab Documentation
- First Year Text Books
- First Year Laboratory Books

15.3 Checkoff Sheet:

See Table 15.1 *LabVIEW Integration Check-Off Sheet* on Page 143.

15.4 Required Use of LabVIEW I/O Functions

For this lab, you are required to use only the following LabVIEW functions for all circuit interaction and control:

- Analog Read
- Analog Write
- Digital Read
- Digital Write

These functions provide the appropriate hardware-level control for the DC motor, solenoid, servo, and stepper motor circuits used in this course. All measurements, control signals, and system interactions must be implemented using only these I/O blocks.

Do not attempt to create software-only solutions or use unsupported LabVIEW features to perform tasks that must be carried out by the hardware. Approaches that bypass the required I/O functions or exceed the capabilities of LabVIEW or the Qwyatt interface board will not meet the lab requirements.

Your LabVIEW block diagram must clearly demonstrate the correct and exclusive use of the Analog Read, Analog Write, Digital Read, and Digital Write functions in your system design.

15.5 LabVIEW Motor Control Integration

Develop a single LabVIEW program to provide a Graphical User Interface (GUI) that meets the following requirements.

15.5.1 DC Motor

1. Speed Control:
   (a) The LabVIEW GUI will allow the user to vary the speed of the DC Motor.
   (b) The LabVIEW program will provide an analog output voltage to the TL494 IC to achieve Speed Control.
   (c) The LabVIEW program will allow the user to control the rotational direction of the DC motor. The motor must be stopped before changing direction.
   (d) The LabVIEW GUI will provide an "Emergency Stop" feature.
2. RPM Monitoring: Choose one of the following options to display the DC motor's RPM within the GUI.
   (a) **Open Loop**: The open loop program will display the predictive RPM of the motor based on the analog output of the speed control. The RPM system accuracy will be verified using a Tachometer.
   (b) **Closed Loop**: The closed loop program will measure the RPM of the motor using an encoder system. The RPM system accuracy will be verified using a Tachometer.

15.5.2 Stepper Motor

Use LabVIEW to control a stepper motor for both of the following scenarios.

1. Scenario One:
   (a) The LabVIEW program and GUI will provide user control of a Stepper Motor.
   (b) The LabVIEW GUI will allow the user to select the step resolution and speed (RPM) of the Stepper Motor.
   (c) The LabVIEW GUI will display the degrees/step, RPM, and a visual representation of the stepper motor position.
2. Scenario Two:
   (a) Create a LabVIEW program that converts a Stepper Motor into a 180° Servo.
   (b) The LabVIEW GUI will allow the user to manipulate the position.
   (c) The LabVIEW GUI will provide a visual representation of the servo position.

15.6 Circuit and LabVIEW Demonstration

1. Be prepared to demonstrate the LabVIEW and circuit control and operation.
2. Be prepared to show and explain the block diagram code and operational logic.

15.7 Key Terms

Define The Following:

- LabVIEW
- GUI

15.8 Troubleshooting Procedure

- Develop a step-by-step troubleshooting procedure for a LabVIEW integrated system.

15.9 Conclusion Instructions

1. Verify that your Check-Off Sheet is completed.
2. Review *Conclusion Guidelines* page vi.
3. Complete your Conclusion.
4. Create an electronic PDF copy of your lab report, making the Check-Off sheet the first page of the PDF.
5. Submit your lab report PDF via Moodle.

15.10 Table Formatting and Data Sets

Table 15.1: LabVIEW Integration Check-Off Sheet

RCET 2252

Clinical Assistant Professor

Timothy Leishman

LabVIEW Integration

Check-Off Sheet

Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
DC Motor: GUI and Speed Control	15.5.1		
DC Motor: Direction and Emergency Stop	15.5.1		
DC Motor: RPM, Closed Loop or Open Loop Control	15.5.1		
Stepper Part A: GUI, Resolution, Speed (RPM), Direction	15.5.2		
Stepper Part B: 180° position control	15.5.2		
Instructor Notes:			

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