

RCET 2253 Instructions

Systems Analog & Digital Laboratory

Advanced Review Copy
September 9, 2024

Timothy S. Leishman
Clinical Assistant Professor
College of Technology
Idaho State University

Contents

Introduction	i
Laboratory Rules	ii
0.1 Safety Rules	ii
0.1.1 Key Safety Principles:	ii
0.2 General Rules	iv
0.2.1 Respectful Conduct	iv
0.2.2 Food and Beverages	iv
0.2.3 Clear Pathways and Work Areas	iv
0.2.4 Instructor's Bench and Office Space	v
0.2.5 Use of Tools	v
0.2.6 Personal Item Work	v
0.2.7 Seating Arrangements	v
0.3 Equipment Rules	v
0.3.1 Equipment Handling	v
0.3.2 Familiarity with Equipment	v
0.3.3 Dealing with Defective Equipment	vi
0.3.4 Proper Shutdown Procedures	vi
0.3.5 Equipment Accessories and Display Care	vi
0.3.6 Precise Measurements	vi
Conclusion Guidelines	vii
0.4 Conclusion Guidelines	vii
0.4.1 Steps for writing a good Conclusion.	vii
0.4.2 Summary	viii
1 Oscilloscope & Test Equipment Familiarization	1
1.1 Objective	1

CONTENTS

1.2	Reference Documents:	1
1.3	Checkoff Sheet:	1
1.4	Lab Instructions:	2
1.4.1	Oscilloscope & Function Generator Controls and Specifications	2
1.4.2	Probe Compensation	3
1.4.3	Vertical Calibration Verification	4
1.4.4	Horizontal Calibration Verification	4
1.4.5	Oscilloscope Measurement Techniques	5
1.4.6	Phase Shift Lissajous Measurements	5
1.4.7	Fast Fourier Transform	6
1.5	Collected Data	7
1.6	Key Terms	8
1.7	Conclusion Instructions	8
1.8	Table Formatting and Data Sets	8
2	RC Circuits	11
2.1	Objective	11
2.2	Reference Documents:	11
2.3	Checkoff Sheet:	11
2.4	Lab Instructions:	12
2.4.1	Frequency Response with Rise Time and Tilt	12
2.4.2	Capacitor Charge Formula and Tau Review	16
2.4.3	Cycles to Stabilization, V_{MAX} , V_{MIN} , & AWV Formulas.	16
2.4.4	Verification of the Cycles to Stabilization, V_{MAX} , & V_{MIN} Formulas. .	16
2.4.5	RC Integration	17
2.4.6	RC Differentiation	18
2.4.7	RC Circuits Sine-wave Instantaneous Voltages	19
2.5	Collected Data	20
2.6	Key Terms	20
2.7	Key Formulas	20
2.8	Conclusion Instructions	20
2.9	Table Formatting and Data Sets	21
3	Multi-Stage Amplifier: Design, Analysis, and Low Critical Frequency	25
3.1	Objectives	25
3.2	Reference Documents:	26

3.3	Checkoff Sheet:	26
3.4	Amplifier Design Parameters	27
3.4.1	Multi-Stage Circuit Design	27
3.4.2	Resistor Standard Values and Circuit Analysis	27
3.4.3	Circuit Measurements	28
3.4.4	Low Frequency Response Calculations	29
3.4.5	Low Frequency Response Measurements	29
3.4.6	Below the Pass-band Output Calculations	29
3.4.7	Below the Pass-band Output Measurements	29
3.5	Collected Data	30
3.6	Key Terms	30
3.7	Key Formulas	30
3.8	Conclusion Instructions	30
3.9	Table Formatting and Data Sets	31
4	Multi-Stage Amplifier: High Critical Frequency and Peaking	34
4.1	Objectives	34
4.2	Reference Documents:	35
4.3	Checkoff Sheet:	35
4.4	Lab Instructions	35
4.4.1	Frequency Critical High Calculations	35
4.4.2	Frequency Critical High Measurements	36
4.4.3	Frequency Critical High adjusted to 2Mhz	36
4.4.4	Above the Pass-band Output Calculations	36
4.4.5	Above the Pass-band Output Measurements	36
4.4.6	Emitter Peaking Calculations:	37
4.4.7	Emitter Peaking Measurements	37
4.4.8	Shunt Peaking Calculations:	38
4.4.9	Shunt Peaking Measurements	38
4.4.10	Series Peaking Calculations:	39
4.4.11	Series Peaking Measurements	39
4.5	Collected Data	40
4.6	Key Terms	40
4.7	Key Formulas	40
4.8	Conclusion Instructions	41
4.9	Table Formatting and Data Sets	41

CONTENTS

5	Push Pull Class AB Amplifiers	43
5.1	Objectives	43
5.2	Reference Documents:	44
5.3	Checkoff Sheet	44
5.4	Lab Instructions:	44
5.4.1	Design: Push-Pull Amplifier	45
5.4.2	Cross-Over Distortion Measurement Procedure	45
5.4.3	Push-Pull Circuit Calibration Procedure	47
5.4.4	Push-Pull Frequency Response Test	48
5.4.5	Design: Single Stage, Universal Biased, Common Emitter Amplifier .	49
5.4.6	Single Stage with Push-Pull, 5-watt Load Test	49
5.4.7	Speaker Test	49
5.5	Collected Data	50
5.6	Key Terms	50
5.7	Key Formulas	50
5.8	Conclusion Instructions	50
5.9	Check-Off Sheet	51
6	Differential Amplifiers	52
6.1	Objectives	52
6.2	Reference Documents:	53
6.3	Checkoff Sheet:	53
6.4	Lab Instructions:	53
6.4.1	Differential Amplifier with Tail Resistor Calculations	53
6.4.2	Differential Amplifier with Tail Resistor Measurements	54
6.4.3	Differential Amplifier with Constant Current Source Calculations . .	54
6.4.4	Differential Amplifier with Constant Current Source Measurements .	55
6.4.5	Single-Ended Differential Amplifier with Gain Control	56
6.4.6	Differential Amplifier Frequency Response	57
6.5	Collected Data	58
6.6	Key Terms	58
6.7	Key Formulas	59
6.8	Conclusion Instructions	59
6.9	Table Formatting and Data Sets	60
7	Operational Amplifiers	63

7.1	Objectives	63
7.2	Reference Documents:	64
7.3	Checkoff Sheet:	64
7.4	Lab Instructions:	64
7.4.1	Operational Amplifier General Information	64
7.4.2	Slew Rate Measurements	65
7.4.3	Differential Amplifier	65
7.4.4	Op-Amp Frequency Response	66
7.4.5	Operational Amplifiers Z_{IN} & Z_{OUT}	67
7.4.6	Operational Amplifier Loading	67
7.4.7	Operational Amplifier Comparators	68
7.4.8	Voltage Bounding	68
7.5	Collected Data	68
7.6	Key Terms	68
7.7	Key Formulas	69
7.8	Conclusion Instructions	69
7.9	Table Formatting and Data Sets	69
8	Operational Amplifiers: DAC, ADC, & Active Filtering	73
8.1	Objectives	73
8.2	Reference Documents	74
8.3	Checkoff Sheet	74
8.4	DAC & ADC	74
8.4.1	Digital to Analog Converter (DAC)	74
8.4.2	Analog to Digital Converter (ADC)	75
8.5	Active Filtering	77
8.5.1	Low-Pass Active Filtering First-Order	77
8.5.2	High-Pass Active Filtering First-Order	77
8.5.3	Band-Pass Active Filtering First-Order	77
8.5.4	Low-Pass Active Filtering Second-Order	78
8.5.5	High-Pass Active Filtering Second-Order	78
8.5.6	Cascaded Band-Pass Active Filtering Second-Order	78
8.5.7	Single-Stage Band-Pass Active Filtering Second-Order	78
8.6	Bessel, Butterworth, & Chebyshev	82
8.6.1	Frequency Response Characteristics & Verification	83
8.7	Collected Data	83

CONTENTS

8.8	Key Terms	83
8.9	Key Formulas	83
8.10	Conclusion Instructions	84
8.11	Table Formatting and Data Sets	84
9	Switching Transistors & Multivibrators	87
9.1	Objectives	87
9.2	Reference Documents	88
9.3	Checkoff Sheet	88
9.4	Switching Transistors	88
9.4.1	Switching Transistor Signal Characteristics	88
9.4.2	Switching Characteristics of the 2N3904	89
9.4.3	Overdrive Switching	89
9.4.4	Commutating Capacitor & Improved Switching	89
9.5	Bipolar Junction Transistor Multivibrators	90
9.5.1	Astable Multivibrator 2N3904 Transistor	90
9.5.2	Astable Multivibrator Improved Rise Time	90
9.5.3	Monostable Multivibrator 2N3904	90
9.5.4	Extreme Duty Cycle Astable Multivibrator	91
9.6	Schmitt Trigger Inverter Astable Multivibrator	91
9.7	555 Timer Multivibrators	92
9.7.1	Astable Multivibrator 555 Timer	92
9.7.2	Monostable Multivibrator 555 Timer	92
9.8	Monostable Multivibrators Integrated Circuits	92
9.8.1	SN74121 & BU4538B	92
9.9	Collected Data	93
9.10	Key Terms	93
9.11	Key Formulas	93
9.12	Conclusion Instructions	93
9.13	Table Formatting and Data Sets	94
10	Linear Regulators & Switching Power Supplies	97
10.1	Objectives	97
10.2	Reference Documents:	98
10.3	Checkoff Sheet:	98
10.4	LM317 Linear Regulators	98

10.4.1	LM317 Specifications and Features	98
10.4.2	Fixed Voltage Regulation	98
10.4.3	Variable Voltage Regulation	99
10.4.4	Fixed Current Regulation	99
10.4.5	Variable Current Regulation	100
10.4.6	LM317 Variable Current & Variable Voltage Circuit.	100
10.5	Heat Sink Calculation Verification	100
10.6	Unregulated Discrete Switch Mode Power Supply BUCK Design	101
10.6.1	The Switch	101
10.6.2	Inductor & Capacitor Calculations	101
10.6.3	PWM Duty Cycle & Load Testing	102
10.7	Regulated Discrete Switch Mode Power Supply BUCK Design	103
10.8	SMPS IC MC34063ACN	104
10.8.1	MC34063ACN Buck	104
10.8.2	MC34063ACN Boost	105
10.8.3	MC34063ACN Inverter	105
10.9	Collected Data	105
10.10	Key Terms	106
10.11	Key Formulas	106
10.12	Conclusion Instructions	106
10.13	Table Formatting and Data Sets	107
11	DC Motors, Solenoids, and Servos	109
11.1	Objectives	109
11.2	Reference Documents:	109
11.3	Checkoff Sheet:	109
11.4	Lab Instructions:	110
11.5	DC Motors (Brushed)	110
11.5.1	DC Brushed Motor theory of operation	110
11.5.2	DC Motor Verification & Initial Testing	110
11.5.3	Switch Operation and PWM Speed Control	110
11.5.4	H-Bridge Direction Control	110
11.5.5	TL494 Analog Voltage Controlled PWM	111
11.5.6	Logic Control Circuitry	111
11.5.7	RPM Monitoring Circuitry	111
11.6	Solenoid	111

CONTENTS

11.6.1 Solenoid Theory of Operation	111
11.6.2 Solenoid Verification and Control Circuit	112
11.7 Servo	112
11.7.1 Servo Theory of Operation	112
11.7.2 Servo Verification and Control Circuit	112
11.8 Electronic Speed Control (ESC)	113
11.8.1 ESC Brushed DC Motor	113
11.8.2 ESC Brushless DC Motor	113
11.9 Collected Data	113
11.10Key Terms	114
11.11Key Formulas	114
11.12Conclusion Instructions	114
11.13Table Formatting and Data Sets	114
12 Stepper Motors	118
12.1 Objectives	118
12.2 Reference Documents:	118
12.3 Checkoff Sheet:	119
12.4 Stepper Motor Control Circuitry	119
12.4.1 Stepper Motor General Operation and Specifications	119
12.4.2 Universal Shift Register SN74194 whole-step	119
12.4.3 JK Flip Flops whole-step	120
12.4.4 JK Flip Flops half-step	120
12.4.5 A4988 Stepper Motor Driver	121
12.4.6 TMC2208 Stepper Motor Driver	121
12.5 Collected Data	122
12.6 Key Terms	122
12.7 Key Formulas	122
12.8 Stepper Motor Trouble Shooting Procedure	122
12.9 Conclusion Instructions	123
12.10Table Formatting and Data Sets	123
13 LabVIEW Integration	126
13.1 Objectives	126
13.2 Reference Documents:	127
13.3 Checkoff Sheet:	127

13.4 LabVIEW Motor Control Integration	127
13.4.1 DC Motor	127
13.4.2 Solenoid	128
13.4.3 Servo	128
13.4.4 Stepper Motor	128
13.5 Circuit and LabVIEW Demonstration	128
13.6 Key Terms	128
13.7 Troubleshooting Procedure	129
13.8 Conclusion Instructions	129
13.9 Table Formatting and Data Sets	129

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:

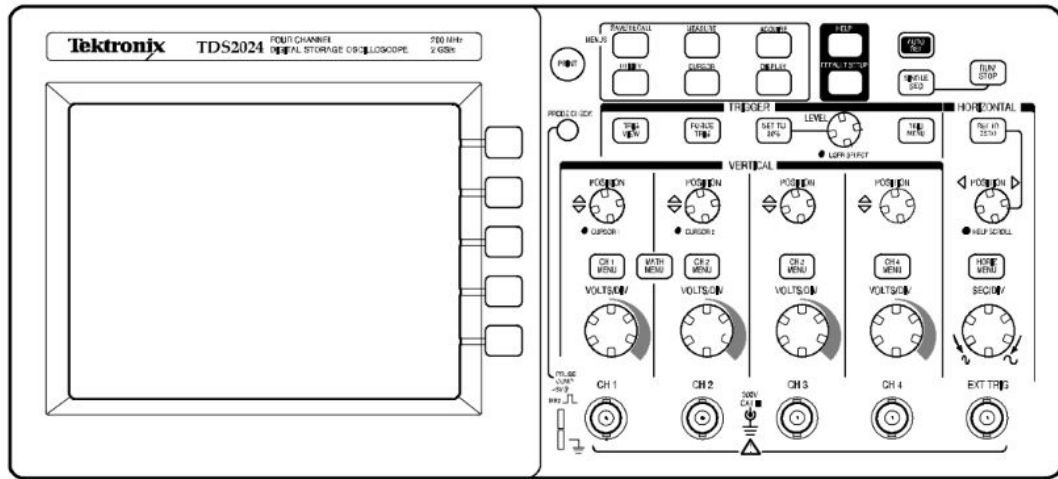
- *Tektronix XYZs of Oscilloscopes* PDF [\[1\]](#)
- *Tektronix TDS Oscilloscope User Manual* PDF [\[2\]](#)
- *Tektronix AFG1022 Arbitrary/Function Generator Quick Start User Manual* PDF [\[3\]](#)
- *Power Supply GPS-4303 User Manual* PDF [\[4\]](#)
- *Tektronix - Get more from your basic oscilloscope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

1.3 Checkoff Sheet:

See Table 1.3 *Oscilloscope & Test Equipment Familiarization Check-Off Sheet* on Page 10.

1.4 Lab Instructions:

1.4.1 Oscilloscope & Function Generator Controls and Specifications



4-channel models

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:

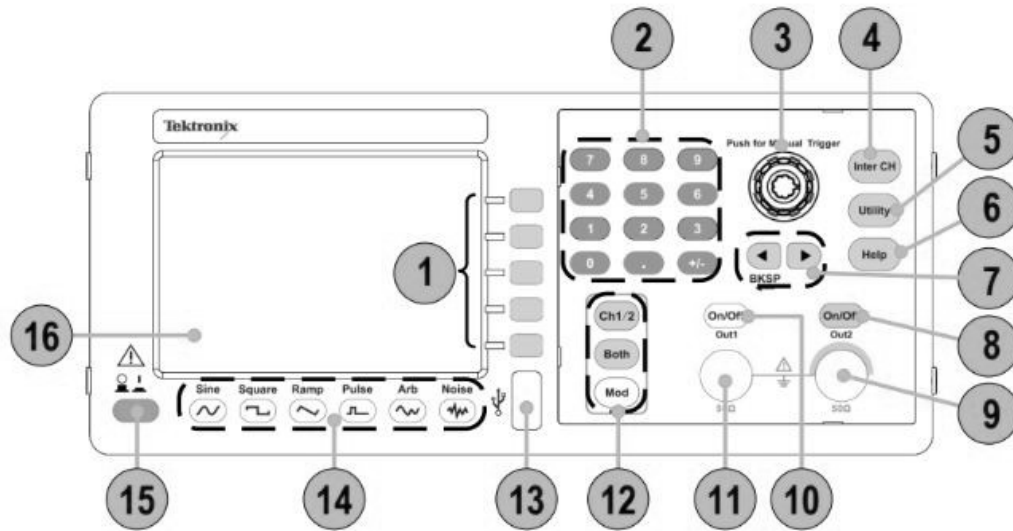


Figure 1.2: AFG1022 Front Panel

- (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 9.

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 9.

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]
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*.
 - (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.

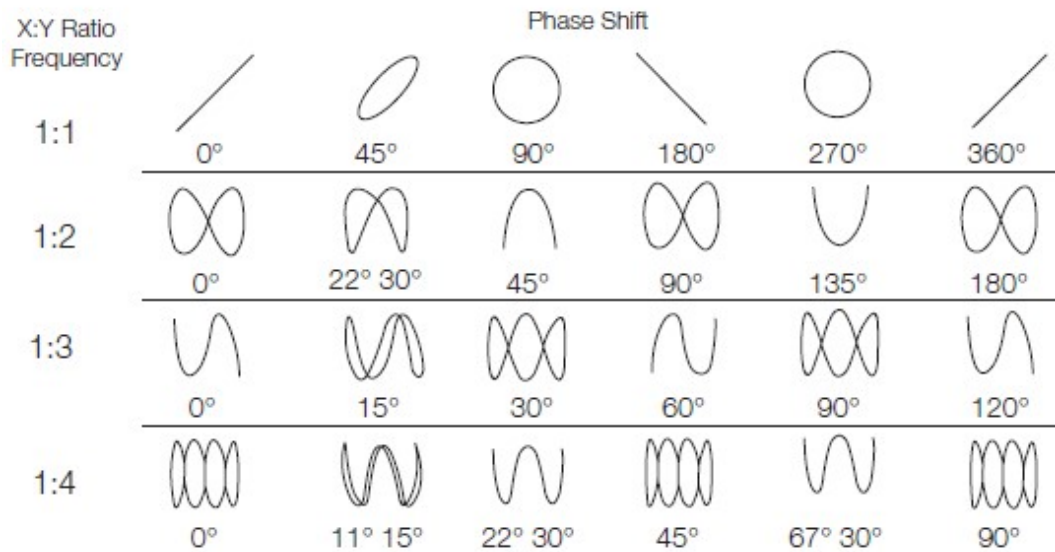


Figure 1.3: Phase Shift Lissajous Measurements

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. 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
 - (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.

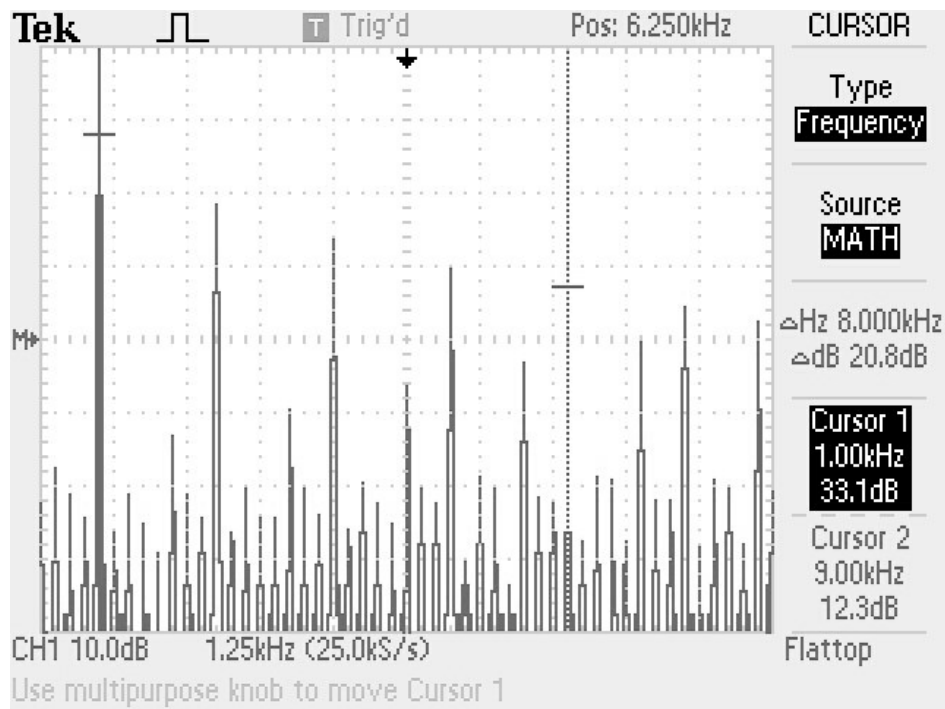


Figure 1.4: FFT Measurements

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.

1.5 Collected Data

- See *Table Formatting and Data Sets* on page 8.
- Include all data sets referenced in the lab.

1.6 Key Terms

Define The Following:

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

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

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

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 24.

2.4 Lab Instructions:

2.4.1 Frequency Response with Rise Time and Tilt

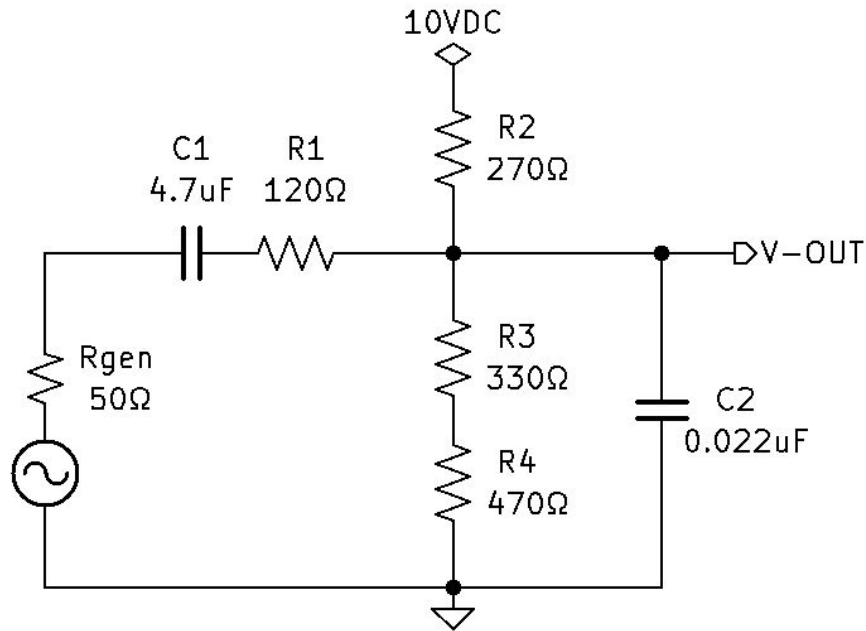


Figure 2.1: RC Circuit 1 (from First Semester)

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 V_{out} 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. FC_H Pulse Theory Measurement:

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

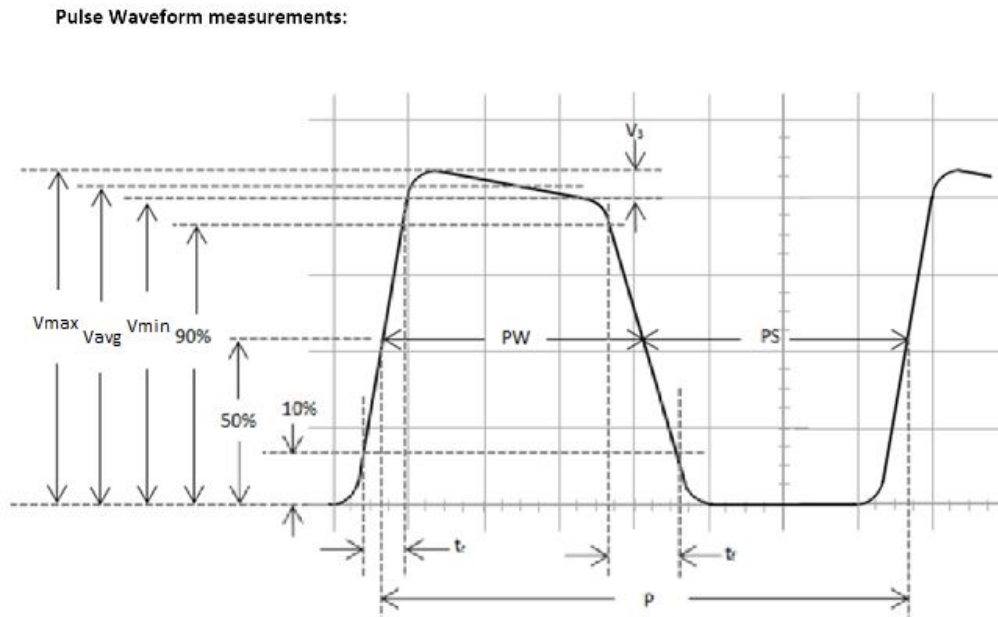


Figure 2.2: Pulse Waveform Measurements

- Draw or attach Figure 2.2 *Pulse Waveforms Measurements*.
- Change the function generator from a sine-wave to a square-wave at 3vpp for Figure 2.1 *RC Circuit 1 (from First Semester)*.
- Adjust the frequency so the waveform tilt is minimized, $\approx 10K_{HZ}$.
- Select Volts/Div Fine and adjust so that the waveform voltage peaks are exactly 5 divisions.
- Center the waveform vertically. See Figure 2.3 *Rise Time Oscilloscope setup 1*.

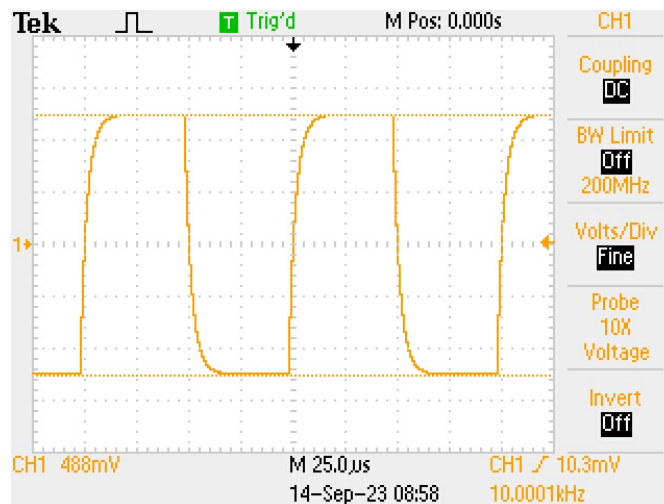


Figure 2.3: Rise Time Oscilloscope setup 1

- (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*.

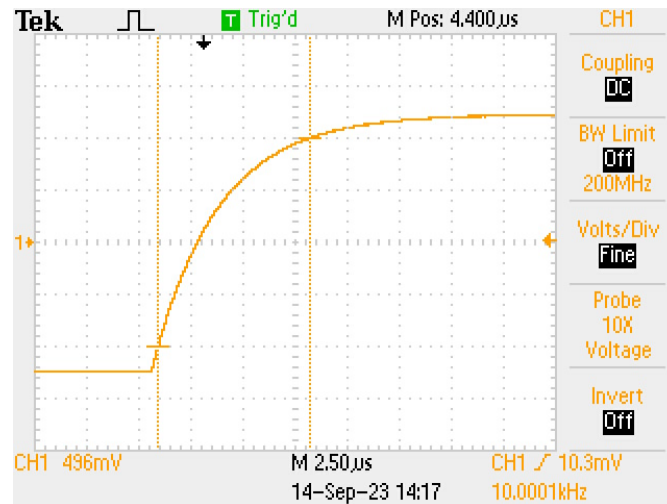


Figure 2.4: Rise Time Measurement

- (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:

- Discuss Low-Frequency Distortion and its causes.
- Assemble circuit Figure 2.1 *RC Circuit 1 (from First Semester)* and set the function generator to 3vpp square-wave.
- Adjust the frequency so the waveform tilt is prominent, $\approx 500_{HZ}$. See Figure 2.5 *Tilt Setup*.
- Adjust the horizontal and vertical controls to accurately measure the tilt. See Figure 2.6 *Tilt Measurement*.
- Measure the Tilt:

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

- (f) Calculate F_{CL} :

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

- Compare the results to the previously measured F_{CL} from step 1.
- Collect measured data. See Table 2.9 *RC Circuit 1 (from First Semester)* (Section 2.4.1). on page 21.

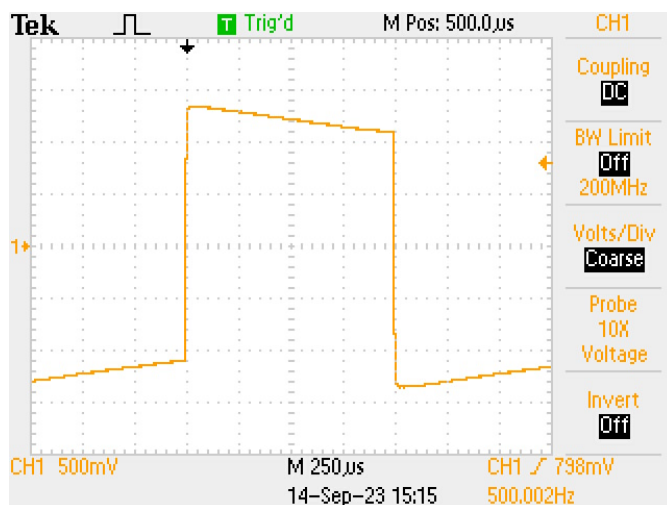


Figure 2.5: Tilt Setup

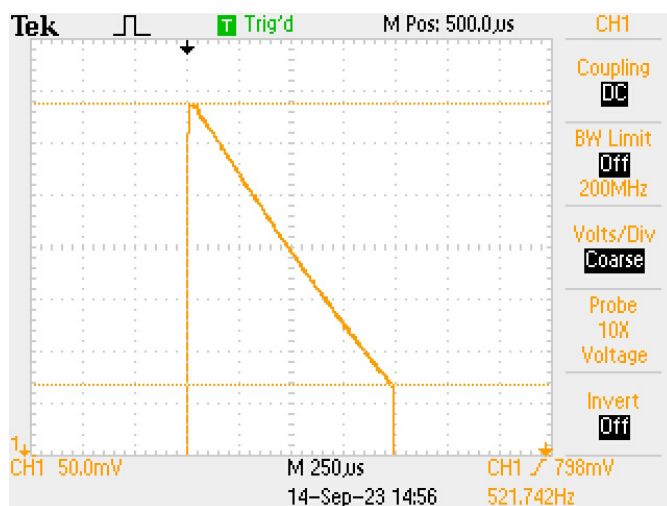


Figure 2.6: Tilt Measurement

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) $V_{gen} = 1K_{HZ}$, Square-Wave, 0v to 10V, 50%DC.
 - (b) $R=1K\Omega$ & $C=1\mu F$
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 V_{gen} .

- (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 21.
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 22.
- 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 22.
- 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) $C = 1\mu F$ & $R = 1K\Omega$.
 - (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 22 and Table 2.6 *RC Circuits Sine-wave Instantaneous Voltage Part 2* on page 23.
- 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 21.
- 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}
<i>Calculated DC</i>						
<i>Measured DC</i>						
Section.2.4.1	V_{GENpp}	V_{OUTpp}	V_{R1pp}	V_{R2pp}	V_{R3pp}	V_{R4pp}
<i>Calculated AC</i>						
<i>Measured AC</i>						
Section.2.4.1	$FC_L Sine$	$FC_H Sine$	<i>Tilt</i>	$Time_{Rise}$	$FC_L Sqr.$	$FC_H Sqr.$
<i>Calculated FC</i>						
<i>Measured FC</i>						

Table 2.2: Cycles to Stabilization (Section 2.4.4).

Section.2.4.4	<i>Cycles</i>	V_{MAX}	V_{MIN}	AWV
<i>Calculated</i>				
<i>Measured</i>				

Table 2.3: RC Integration (Section 2.4.5).

Section.2.4.5	C	$Cycles$	V_{MAX}	V_{MIN}	AWV
<i>Calculated</i>					
<i>Measured</i>					

Table 2.4: RC Differentiation (Section 2.4.6).

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

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	$V_C \angle^\circ$	$V_R \angle^\circ$
<i>Calculated</i>	$10V_P$	$1\mu F$	$1K\Omega$			
<i>Measured</i>						

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

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

Table 2.7: RC Circuits Check-Off Sheet

<p>RCET 2252</p> <p>Clinical Assistant Professor</p> <p>Timothy Leishman</p> <p><i>RC Circuits</i></p> <p>Check-Off Sheet</p>			
Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>RC Circuit 1 (from First Semester)</i>	2.4.1		
<i>Verification Cycles to Stabilization</i>	2.4.4		
<i>RC Integration</i>	2.4.5		
<i>RC Differentiation</i>	2.4.6		
<i>RC Circuits Sine-wave Inst. Voltages</i>	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 33.

3.4 Amplifier Design Parameters

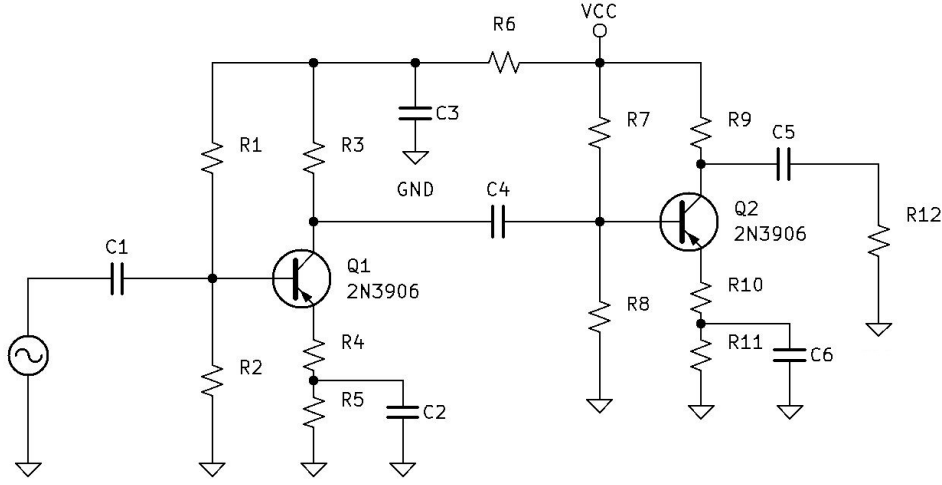


Figure 3.1: Two Stage Amplifier Design

Design Parameters:

- $V_{CC} = -25V$
- Q_1 and Q_2 , $\Delta V = -10$
- $I_{R8} = 10 \times IB_{Q2}$
- P_{Q1} & $P_{Q2} = 312.5mW$
- $\beta = 200$, for Q_1 and Q_2 ,
- $R_{12} = 10 \times R_9$
- Optimized Biasing
- $I_{R2} = 10 \times IB_{Q1}$
- $R_3 = \frac{RL_{EquivalentQ1}}{10}$

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 $V_{out_{MAXP}}$ and $V_{in_{MAXP}}$.

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 $V_{out_{MAXp}}$ and $V_{in_{MAXp}}$.
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 $V_{out_{MAXp}}$.
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 31.
- Include all the data sets referenced in the lab.

3.6 Key Terms

Define The Following:

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

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

	<i>Calculated</i>	<i>Measured</i>		<i>Calculated</i>	<i>Measured</i>		<i>Calculated</i>
V_{CC}			$V_{CE_{Q1}}$			P_{Q1}	
			$V_{CE_{Q2}}$			P_{Q2}	
R_1			V_{R1}			P_{R1}	
R_2			V_{R2}			P_{R2}	
R_3			V_{R3}			P_{R3}	
R_4			V_{R4}			P_{R4}	
R_5			V_{R5}			P_{R5}	
R_6			V_{R6}			P_{R6}	
R_7			V_{R7}			P_{R7}	
R_8			V_{R8}			P_{R8}	
R_9			V_{R9}			P_{R9}	
R_{10}			V_{R10}			P_{R10}	
R_{11}			V_{R11}			P_{R11}	
R_{12}			V_{R12}			P_{R12}	

Table 3.2: Multi-Stage AC Data.

	<i>Calculated</i>	<i>Measured</i>		<i>Calculated</i>	<i>Measured</i>
Z_{in}			Z_{out}		
$V_{in_{PP}}$			$V_{out_{pp}}$		
ΔV_{Q1}			ΔV_{Q2}		
ΔV_{Total}					
$V_{in_{MAXp}}$			$V_{out_{MAXp}}$		

Table 3.3: Multi-Stage Low Frequency Response Data.

<i>Frequency Response Low, calculated capacitance values for 1KHz.</i>					
	<i>Calculated</i>		<i>Calculated</i>	<i>Std. Value</i>	$F_{c_{LOW}Std.V}$
$R_{th_{C1}}$		$C1$			
$R_{th_{C2}}$		$C2$			
$R_{th_{C3}}$		$C3$			
$R_{th_{C4}}$		$C4$			
$R_{th_{C5}}$		$C5$			
$R_{th_{C6}}$		$C6$			
<i>Calculated $F_{c_{LOW}}$ using standard value capacitors $F_{c_{LOW}Total}$:</i>					
<i>Sine-wave Analysis Measurement:</i>					
$F_{c_{LOW}Total}$:					
<i>Square-wave Analysis Measurement:</i>					
<i>Tilt</i>		<i>PW</i>		$F_{c_{LOW}Total}$:	
<i>Phase and dB Calculations and Measurements</i>					
	<i>Freq.</i>	<i>Calc. ϕ</i>	<i>Meas. ϕ</i>	<i>Calc. dB</i>	<i>Meas. dB</i>
$F_{c_{LOW}}$					
$1^{st} Octave$					
$1^{st} Decade$					

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 $C_{total_{In}}$, $C_{total_{Mid}}$, and $C_{total_{Out}}$. 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 42.

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) $RTH_{C_{TotalIN}}$, $RTH_{C_{TotalMID}}$, $RTH_{C_{TotalOUT}}$
- (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 2Mhz

1. Modify the circuit by adding parallel capacitance at the load to achieve a new frequency critical high equal to 2Mhz, $FC_{High} = 2Mhz$.
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: $\Delta v = \frac{V_{out}}{V_{in}}$
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: $\Delta v = \frac{V_{out}}{V_{in}}$
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 $FC_{H_{ShuntP}}$ 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 41.
- Include all the data sets referenced in the lab.

4.6 Key Terms

Define The Following:

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

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}	$Imp.(K)$
<i>Calculated</i>				
<i>Measured</i>				
Sec.4.4.8	FC_{HIGH}	L_{ShuntP}	FCH_{ShuntP}	$Imp.(K)$
<i>Calculated</i>				
<i>Measured</i>				
Sec.4.4.10	FC_{HIGH}	$L_{SeriesP}$	$FCH_{SeriesP}$	$Imp.(K)$
<i>Calculated</i>				
<i>Measured</i>				

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

<p>RCET 2252</p> <p>Clinical Assistant Professor</p> <p>Timothy Leishman</p> <p><i>Multi-Stage Amplifier Part 2</i></p> <p>Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>FC_{High} Calculations and Measurement</i>	4.4.1		
<i>FC_{High} Calibrated</i>	4.4.3		
<i>Emitter Peaking Calculations</i>	4.4.6		
<i>Emitter Peaking Measurements</i>	4.4.7		
<i>Shunt Peaking Calculations</i>	4.4.8		
<i>Shunt Peaking Measurements</i>	4.4.9		
<i>Series Peaking Calculations</i>	4.4.10		
<i>Series Peaking Measurements</i>	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 51.

5.4 Lab Instructions:

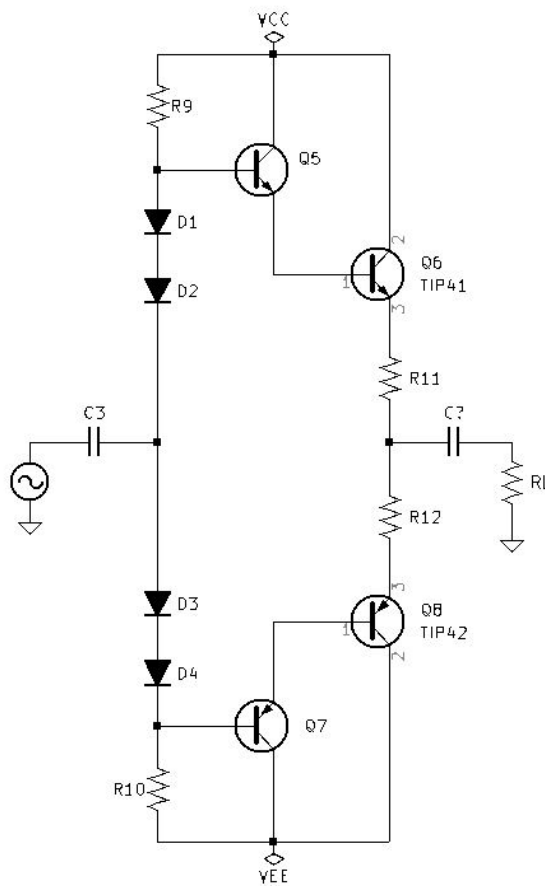


Figure 5.1: Push Pull Amplifier.

5.4.1 Design: Push-Pull Amplifier

1. See Figure 5.1 *Push Pull Amplifier* on page 44.
2. Design a Push-Pull circuit to accept an input signal from the output of the previously designed Constant Current Source Differential Amplifier with Gain Control. See Chapter 6 Section 6.4.3 Differential Amplifiers Lab.
3. Design Parameters:
 - (a) $V_{CC} = 25V$
 - (b) $V_{EE} = 0V$
 - (c) The Push-Pull must be capable of driving an 8Ω , 5 watt load.
4. Include a properly labeled schematic.
5. Including the following calculations:

• resistors	• capacitors	• Z_{in}
• voltages	• $V_{out_{P_{max}}}$	• Z_{out}
• powers	• $V_{in_{P_{max}}}$	• heat sinks
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.

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 46.
 - (c) Apply the DC voltages V_{CC} & V_{EE} to the circuit.
 - (d) Measure DC voltages. Verify that V_{R11} & V_{R12} 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.

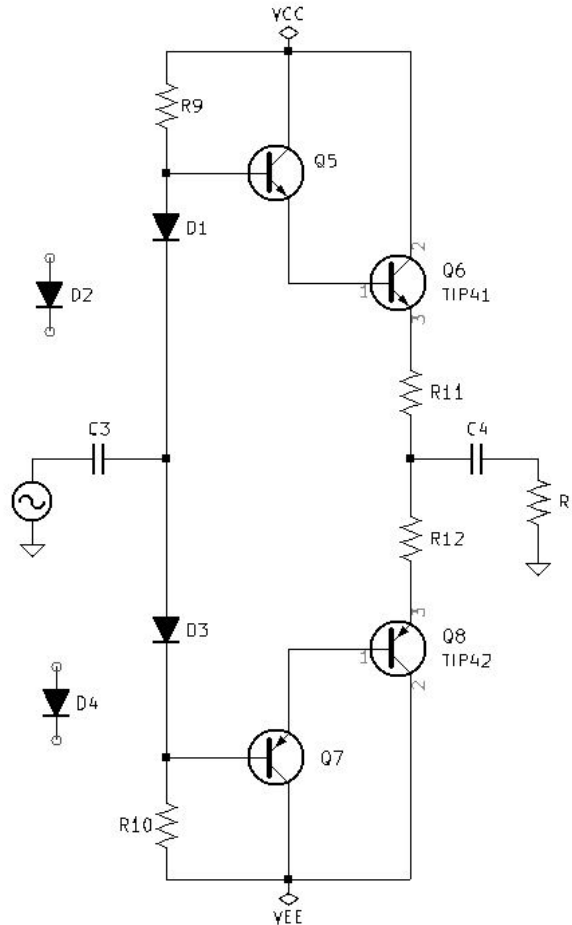


Figure 5.2: Push Pull Amplifier Cross-Over Distortion Test Circuit.

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

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

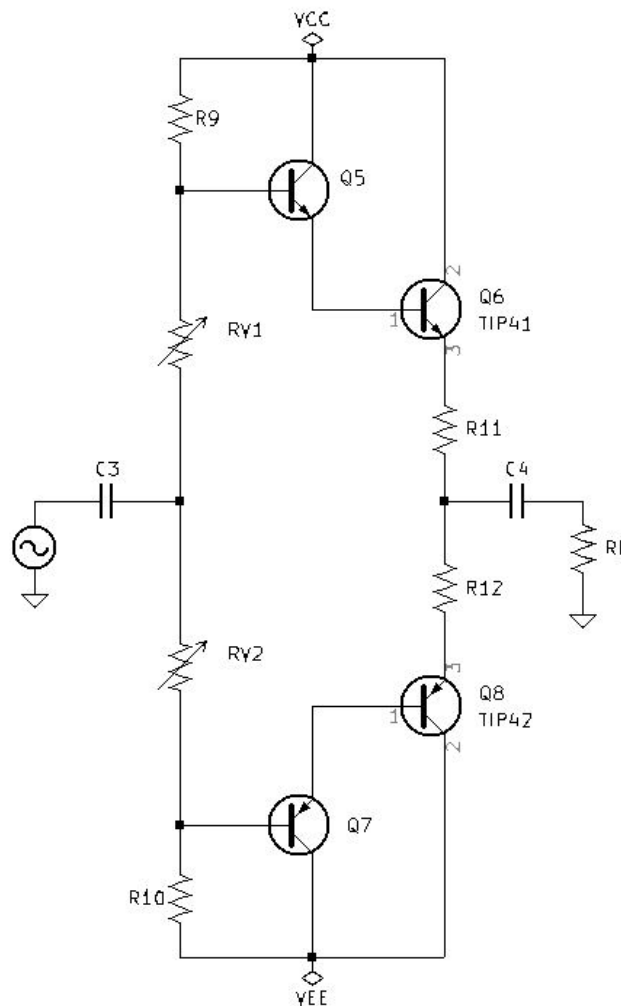


Figure 5.3: Push Pull Amplifier Calibration Circuit.

1. Define Shoot-Through.
2. 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 Shoot-Through when a 0v input signal is applied. Too much shoot-through will damage the circuit components and not enough will cause excessive cross-over distortion.
3. Check the circuit for a minimum amount of shoot-through 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.

4. See Figure 5.3 *Push Pull Amplifier Calibration Circuit* on page 47. Replace the diodes D1 and D2 with a variable 10-turn variable resistor. This resistor can be calculated using the formula $R_{var} \approx \frac{1.4V}{I_{Diode}}$. Make sure the variable resistor is capable of going just above the calculated resistance. In the circuit, replace diodes D1 and D2 with the 10-turn variable resistor and adjust the variable resistor to 0Ω . Repeat this step for diodes D3 and D4.
5. With both variable resistors set to 0Ω and the input signal tied to ground, measure VR11 and VR12. These voltages should initially be 0V when power is applied to the circuit.
6. Adjust RV_1 (the variable resistor that replaced D1 and D2) until I_{R11} is 50mA. Repeat the process with RV_2 & I_{R12} . Verify that both VR_{11} & VR_{12} are equal and the current equal approximately 50mA.
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 measurement.
 - (c) Measure $V_{out}P_{Max}$.
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 appropriate circuit adjustments and repeat 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.
3. Determine the necessary voltage gain needed to provide 5 watts of power to an 8Ω load.
4. Verify $V_{out}P_{Max}$ of the Single Stage Amplifier
5. Verify the Frequency Response of the Single Stage Amplifier.

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 51.
- Include all the data sets referenced in the lab.

5.6 Key Terms

Define The Following:

- | | |
|-----------------------|---------------------------|
| • Class AB Amplifier | • Cross-Over Distortion |
| • Push-Pull Amplifier | • Shoot-Through |
| • Head Room | • 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

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>Push Pull Class AB Amplifiers</i> Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>Push-Pull Amplifier Calculations</i>	5.4.1		
<i>Cross-Over Distortion Measurements</i>	5.4.2		
<i>Push-Pull Circuit Calculation</i>	5.4.3		
<i>Push-Pull 5-watt Load Test</i>	??		
<i>Push-Pull Frequency Response</i>	5.4.4		
<i>Single-Stage & Push-Pull: 8Ω ΔV and Freq.</i>	5.4.6		
<i>Speaker Test - Orange Blossom Special</i>	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 62.

6.4 Lab Instructions:

6.4.1 Differential Amplifier with Tail Resistor Calculations

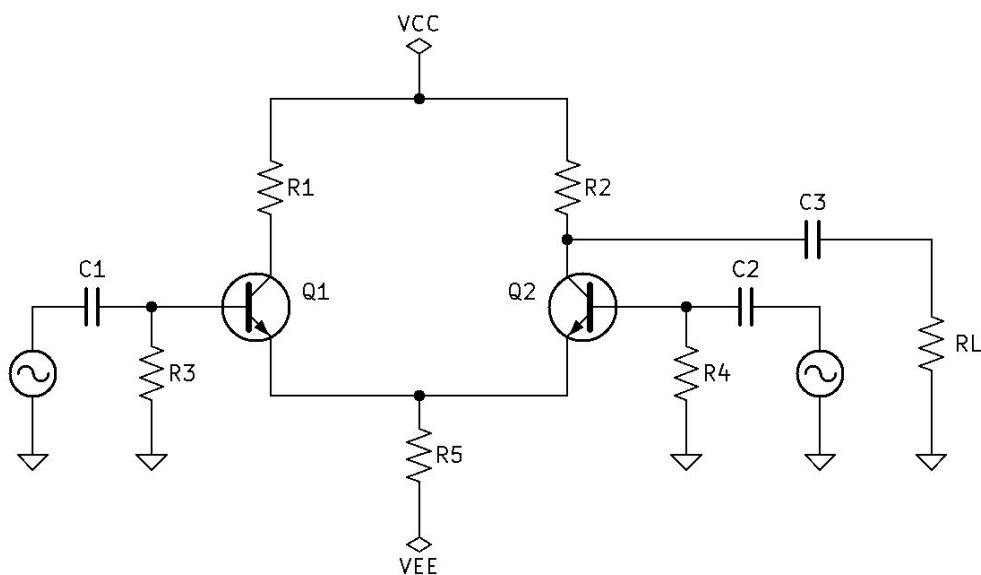


Figure 6.1: Differential Amplifier with Tail Resistor

- Design a Differential Amplifier with a Tail Resistor using the following parameters:
 - See Figure 6.1
 - $VCC = 20V_{DC}$ & $VEE = -20V_{DC}$
 - Biasing must be optimized at 45%, 45%, 10%.
 - 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

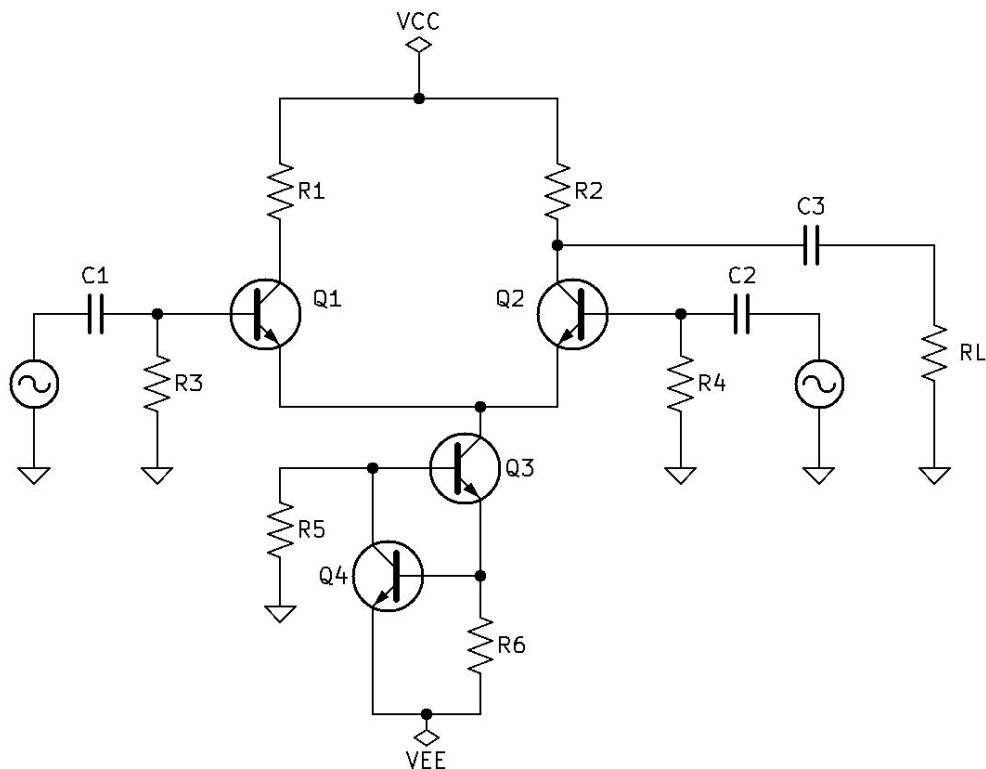


Figure 6.2: Differential Amplifier with Constant Current Source

- (b) $V_{CC} = 20V_{DC}$ & $V_{EE} = -20V_{DC}$
- (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} , ($R_L = R_C \times 10$).
- (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. 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 ($\Delta_V = -10$).
 4. Assemble the circuit and measure the Single-Ended Inverting Gain.

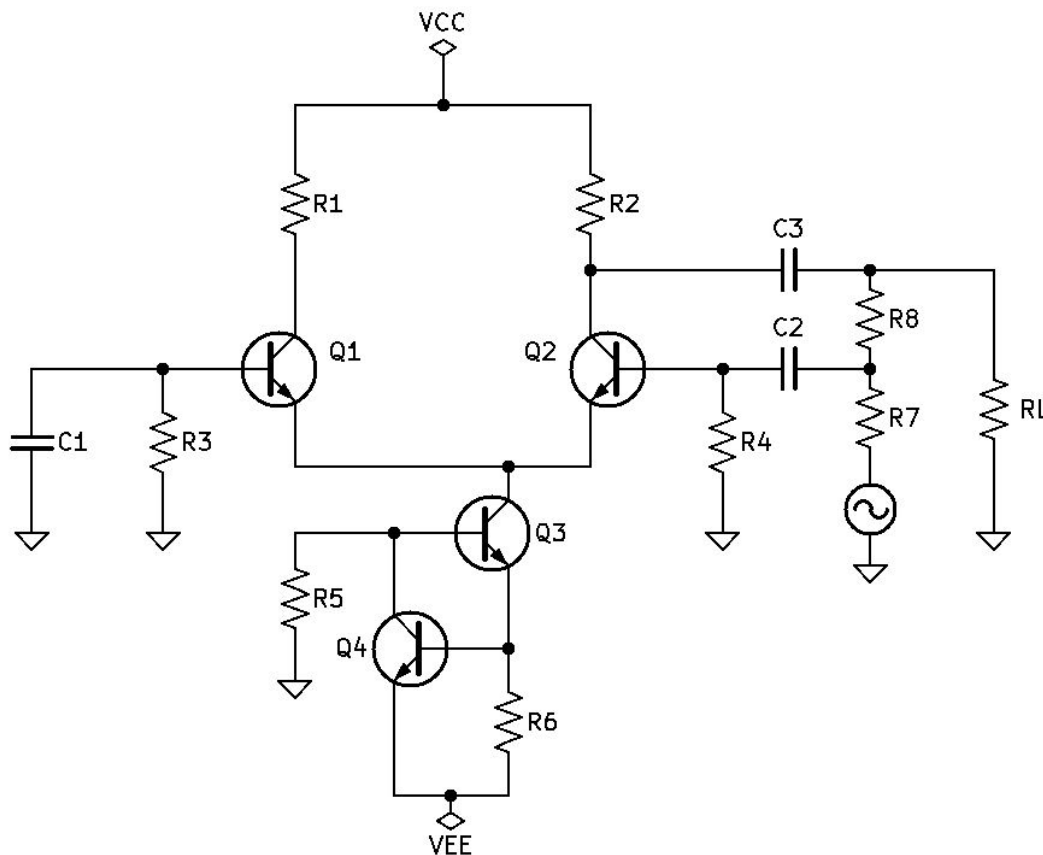


Figure 6.3: Single-Ended Inverting Diff Amp with Gain Control.

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.

6.4.6 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.
3. Repeat the measurement for the Single-Ended Inverting Diff Amp with a gain of $\Delta_V = -10$.

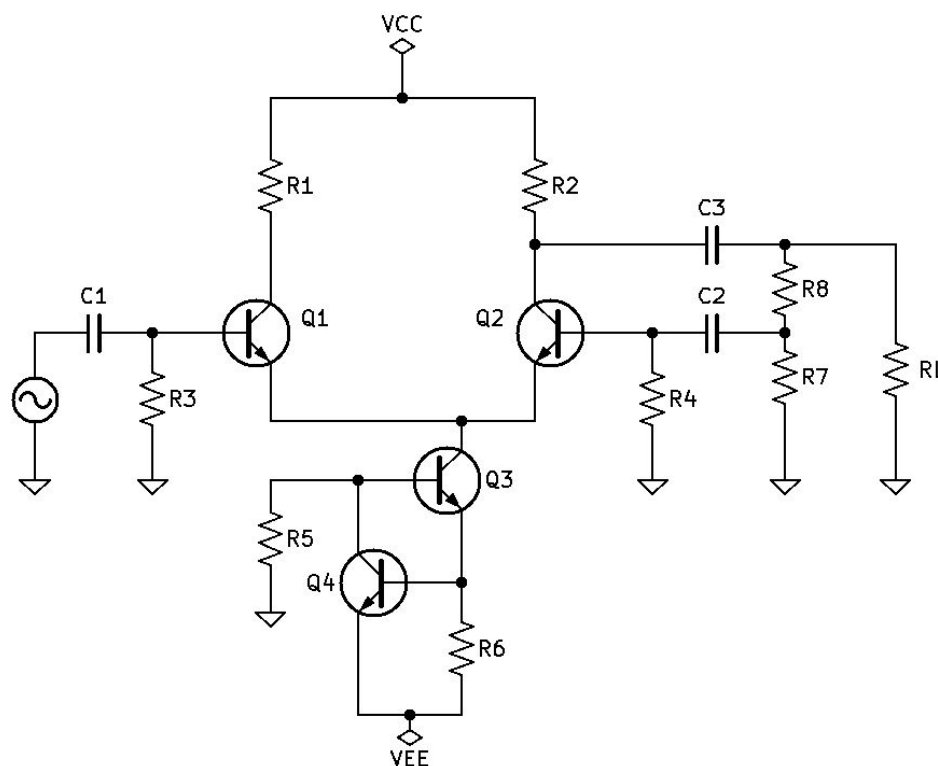


Figure 6.4: Single-Ended Non-Inverting Diff Amp with Gain Control.

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.

6.5 Collected Data

- See *Table Formatting and Data Sets Examples* on page 60.
- 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}
<i>Calculated</i>					
<i>Measured</i>					
Sec.6.4.1 R_{Tail}	$R1 \text{ \& } R2$	$R3 \text{ \& } R4$	$R5$	RL	
<i>Calculated</i>					
<i>Measured</i>					
Sec.6.4.1 R_{Tail}	$P_{R1} \text{ \& } P_{R2}$	$P_{R3} \text{ \& } P_{R4}$	P_{R5}	P_{RL}	$P_{Q1} \text{ \& } P_{Q2}$
<i>Calculated</i>					
<i>Measured</i>					
Sec.6.4.2 R_{Tail}	Z_{IN}	Z_{OUT}	ΔV_{CE}	ΔV_{CC}	ΔV_{CB}
<i>Calculated</i>					
<i>Measured</i>					
Sec.6.4.2 R_{Tail}	ΔV_{CCCB}	ΔV_{CM}	ΔV_{Diff}	$CMRR$	$CMRR_{dB}$
<i>Calculated</i>					
<i>Measured</i>					

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

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

Table 6.3: Differential Amplifiers Check-Off Sheet

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>Differential Amplifiers</i> Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>Diff Amp with R_{Tail} Calculations</i>	6.4.1		
<i>Diff Amp with R_{Tail} Measurements</i>	6.4.2		
<i>Diff Amp with CCS Calculations</i>	6.4.3		
<i>Diff Amp with CCS Measurements</i>	6.4.4		
<i>Diff Amp with Gain Control</i>	6.4.5		
<i>Diff Amp Frequency Response</i>	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 72.

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 69.
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 69.

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

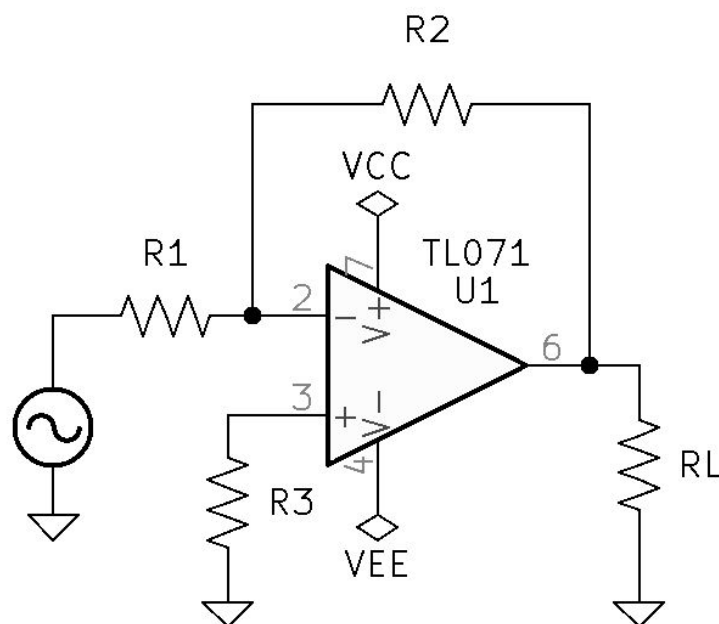


Figure 7.1: Inverting Operational Amplifier Circuit

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 70.
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 69.
- Include all the data sets referenced in the lab.

7.6 Key Terms

Define The Following:

- | | |
|--------------------|--------------------|
| • Ideal Op-Amp | • FAB |
| • <i>Slew Rate</i> | • $GBWP$ |
| • Rail to Rail | • Comparator |
| • Δ_{OL} | • 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	<i>LM741</i>	<i>TL071</i>	<i>MCP6002</i>
<i>Data Specification</i>			
<i>Measured</i>			

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

<i>Transistor Diff-Amp</i>	ΔV_{CE}	ΔV_{CCCB}	ΔV_{CM}	ΔV_{Diff}	$CMRR_{dB}$
<i>Measured</i>					
<i>TL071 Op Amp</i>	ΔV_-	ΔV_+	ΔV_{CM}	ΔV_{Diff}	$CMRR_{dB}$
<i>Calculated</i>					
<i>Measured</i>					

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

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

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

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

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

<i>Three-Stage</i>	$R1$	$R2$	$R3$	$R4$	$R5$
<i>Calculated</i>					
<i>Measured</i>					
<i>Three-Stage</i>	$R6$	$R7$	$R8$	$R9$	RL
<i>Calculated</i>					
<i>Measured</i>					
<i>Three-Stage</i>	VCC	VEE	$V_{OUT.U1}$	$V_{OUT.U2}$	$V_{OUT.U3}$
<i>Calculated</i>					
<i>Measured</i>					
<i>Two-Stage</i>	ΔV_{U1}	ΔV_{U2}	ΔV_{U3}	ΔV_{Total}	
<i>Calculated</i>					
<i>Measured</i>					

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

Section 7.4.4	<i>Single – Stage</i>	<i>Two – Stage</i>	<i>Three – Stage</i>
ΔV_{Total} <i>Calculated</i>			
ΔV_{Total} <i>Measured</i>			
FC_{LOW} <i>Calculated</i>			
FC_{LOW} <i>Measured</i>			
FC_{HIGH} <i>Calculated</i>			
FC_{HIGH} <i>Measured</i>			

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

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>Operational Amplifiers</i> Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>Slew Rate Measurements</i>	7.4.2		
<i>Differential Amplifier Measurements</i>	7.4.3		
<i>Op-Amp Frequency Response</i>	7.4.4		
<i>Op-Amp Loading</i>	7.4.6		
<i>Op-Amp Comparator</i>	7.4.7		
<i>Voltage Bounding</i>	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 multi-meters (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 75.
 - (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.

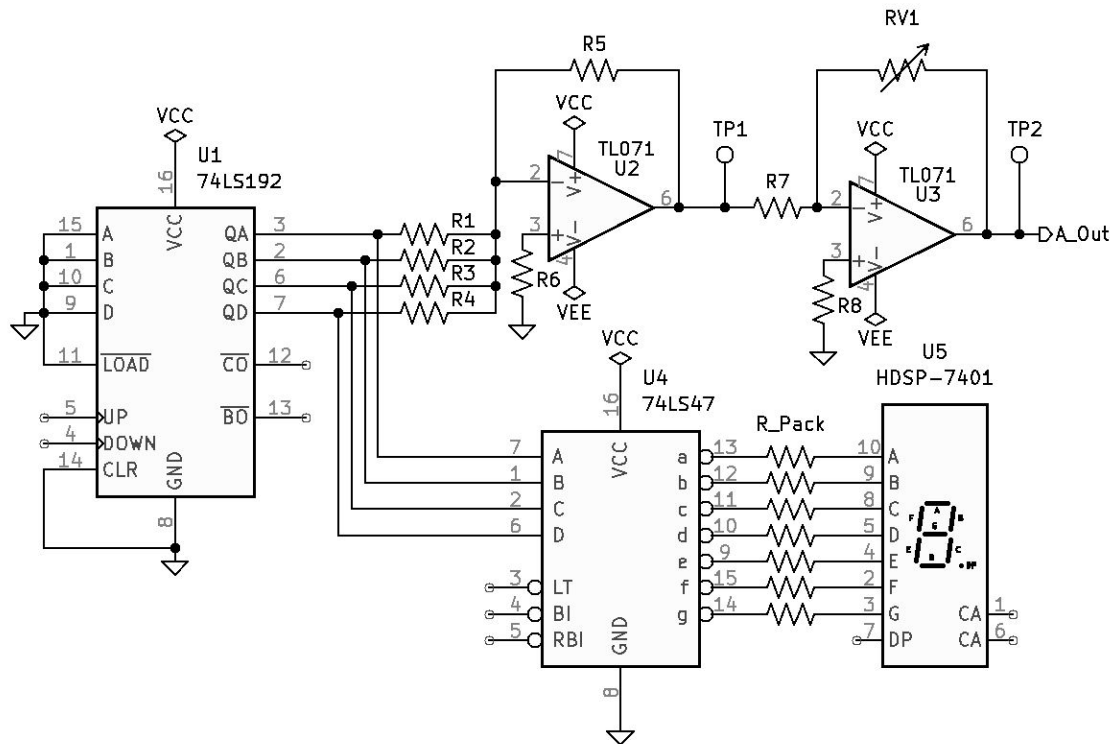


Figure 8.1: DAC Engineering Department Prototype Circuit.

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 76.
 - (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.

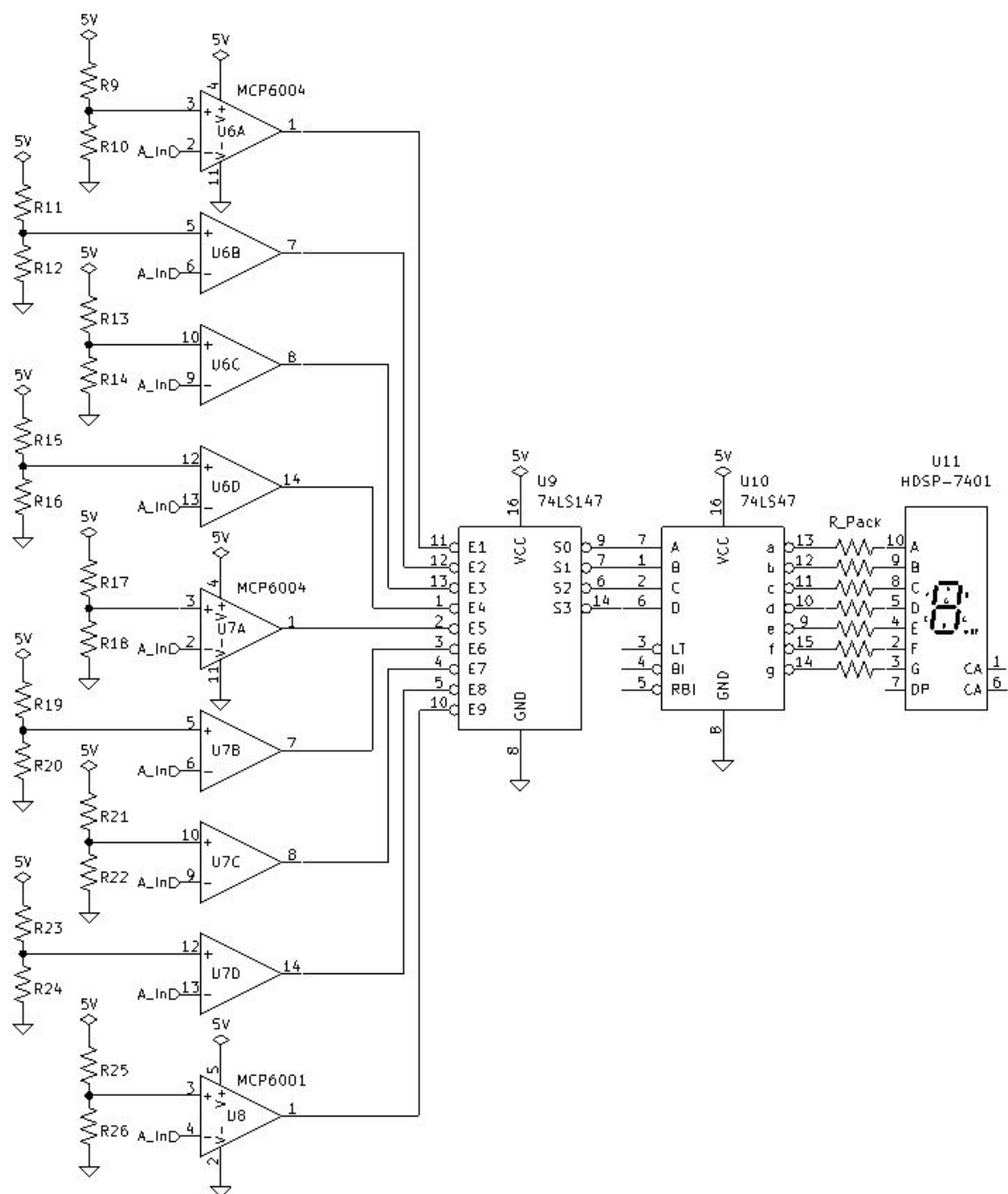


Figure 8.2: ADC Engineering Department Prototype Circuit.

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 79.
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 84.

8.5.2 High-Pass Active Filtering First-Order

1. See Figure 8.4 *High-Pass First-Order Active Filtering Circuit* on page 79.
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 84.

8.5.3 Band-Pass Active Filtering First-Order

1. See Figure 8.5 *Band-Pass First-Order Active Filtering Circuit* on page 80.
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 84.

8.5.4 Low-Pass Active Filtering Second-Order

1. See Figure 8.6 *Low-Pass Second-Order Active Filtering Circuit* on page 80.
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 8.3 on page 85.

8.5.5 High-Pass Active Filtering Second-Order

1. See Figure 8.7 *High-Pass Second-Order Active Filtering Circuit* on page 81.
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 8.3 on page 85.

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 8.3 on page 85.

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 81.
2. Calculate a Single-Stage Band-Pass Second-Order Active Filter circuit with a Q of 1 and a resonant frequency of $10Khz$.

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 8.3 on page 85.
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.

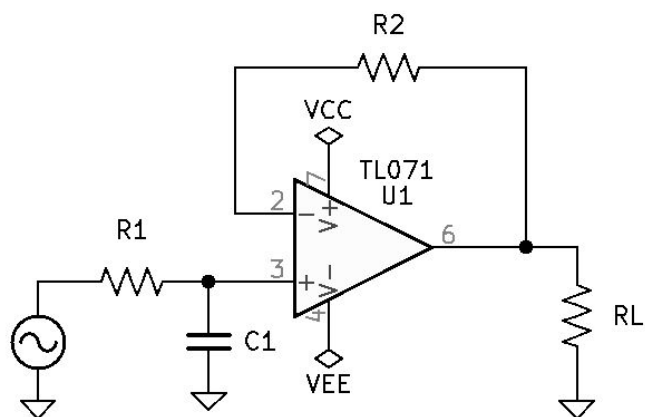


Figure 8.3: Low-Pass First-Order Active Filtering Circuit.

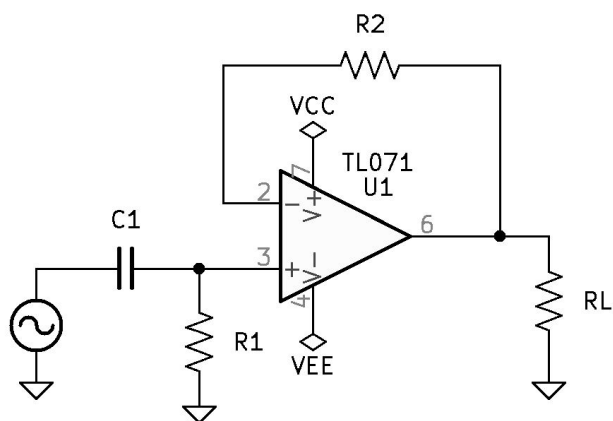


Figure 8.4: High-Pass First Order Active Filtering Circuit.

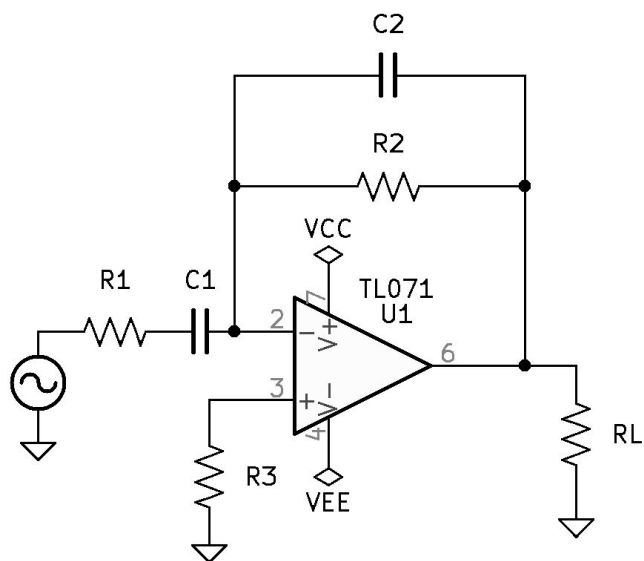


Figure 8.5: Band-Pass First-Order Active Filtering Circuit.

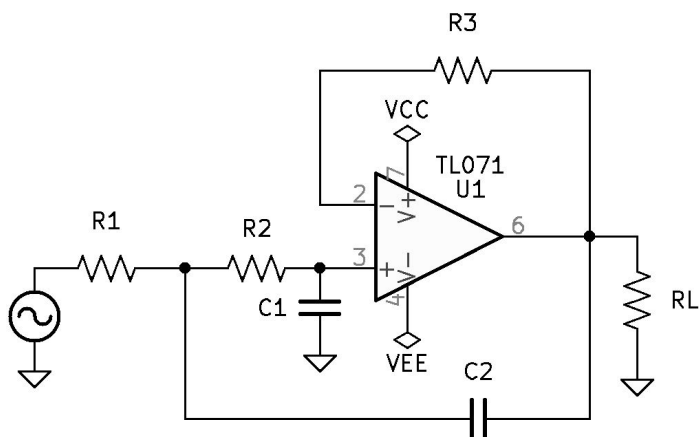


Figure 8.6: Low-Pass Second-Order Active Filtering Circuit.

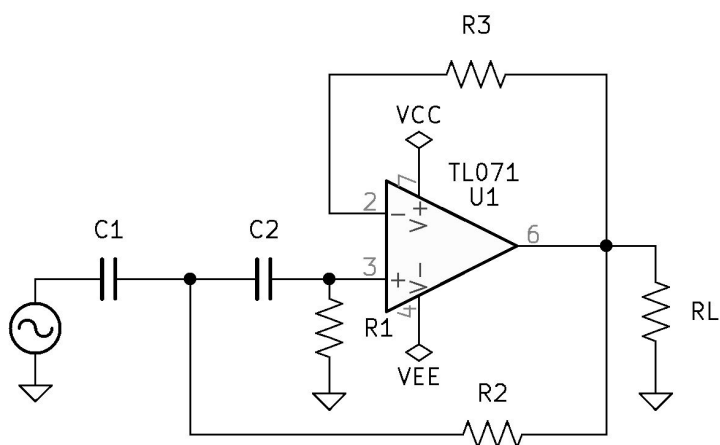


Figure 8.7: High-Pass Second-Order Active Filtering Circuit.

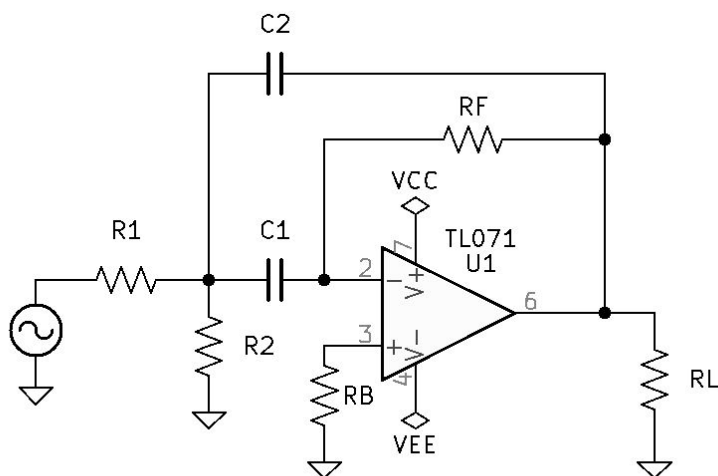


Figure 8.8: Single Stage Band-Pass Second-Order Active Filtering Circuit.

8.6 Bessel, Butterworth, & Chebyshev

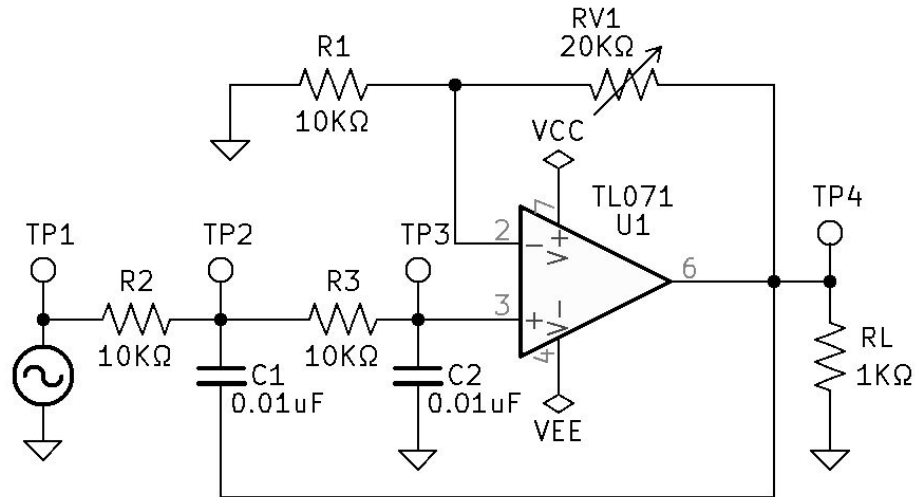


Figure 8.9: Bessel, Butterworth, Chebyshev Frequency Response Test Circuit.

Table 8.1: Bessel, Butterworth, Chebyshev Data.

Figure 8.9	TP1	TP2	TP3	$\frac{TP1}{TP3}$	RV1	TP4	ΔV
<i>Bessel</i>	$2v_{pp}$	$1.414v_{pp}$	$1v_{pp}$	2	0.0Ω	$1v_{pp}$	1
<i>Bessel</i>	$1.73v_{pp}$	$1.414v_{pp}$	$1v_{pp}$	1.73	$2.68K\Omega$	$1.268v_{pp}$	1.268
<i>Butterworth</i>	$1.414v_{pp}$	$1.414v_{pp}$	$1v_{pp}$	1.414	$5.86K\Omega$	$1.586v_{pp}$	1.586
<i>Chebyshev</i>	$1v_{pp}$	$1.414v_{pp}$	$1v_{pp}$	1	$10K\Omega$	$2v_{pp}$	2
<i>Chebyshev</i>	$0.5v_{pp}$	$1.414v_{pp}$	$1v_{pp}$	0.5	$15K\Omega$	$2.5v_{pp}$	2.5
<i>Oscillator</i>	$0v_{pp}$				$20K\Omega$	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 84.
- Include all the data sets referenced in the lab.

8.8 Key Terms

Define The Following:

- | | | | |
|-------------|--------------------|--------------------------|---------------|
| • DAC | • Octave | • First-Order Filtering | • Bessel |
| • ADC | • Decade | | |
| • High Pass | • Second Octave | • Second-Order Filtering | • Butterworth |
| • Low Pass | • Second Decade | | |
| • Band Pass | • Active Filtering | • Cascaded | • 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	<i>Calc.</i>	<i>Meas.</i>	<i>Calc.</i>	<i>Meas.</i>	<i>Calc.</i>	<i>Meas.</i>
FC_{LOW}			20_{HZ}		20_{HZ}	
FC_{HIGH}	$20K_{HZ}$				$20K_{HZ}$	
F_{Octave}						
$F_{2.Octave}$						
F_{Decade}						
$F_{2.Decade}$						
$V_{ppPassBand}$						
V_{ppFC}						
$V_{ppOctave}$						
$V_{pp2.Octave}$						
$V_{ppDecade}$						
$V_{pp2.Decade}$						
$dB_{PassBand}$						
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		Single Stage BP	
Second Order	<i>Calc.</i>	<i>Meas.</i>	<i>Calc.</i>	<i>Meas.</i>	<i>Calc.</i>	<i>Meas.</i>	<i>Calc.</i>	<i>Meas.</i>
FC_{LOW}			20_{HZ}		20_{HZ}			
FC_{HIGH}	$20K_{HZ}$				$20K_{HZ}$			
F_{Octave}								
F_{2_Octave}								
F_{Decade}								
F_{2_Decade}								
$V_{ppPassBand}$								
V_{ppFC}								
$V_{ppOctave}$								
V_{pp2_Octave}								
$V_{ppDecade}$								
V_{pp2_Decade}								
$dB_{PassBand}$								
dB_{FC}								
dB_{Octave}								
dB_{2_Octave}								
dB_{Decade}								
dB_{2_Decade}								

Table 8.4: Operational Amplifiers: DAC, ADC, & Active Filtering Check-Off Sheet

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>DAC, ADC, & Filtering Check-Off Sheet</i></p> <p style="text-align: center;">Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>DAC Calculations</i>	8.4.1		
<i>DAC Measurements</i>	8.4.1		
<i>ADC Calculations</i>	8.4.2		
<i>ADC Measurements</i>	8.4.2		
<i>First-Order Active Filtering</i>	8.5.1 to 8.5.3		
<i>Second-Order Active Filtering</i>	8.5.4 to 8.5.7		
<i>Bessel, Butterworth, Chebyshev</i>	8.6.1		
Instructor Notes:			

Lab 9

Switching Transistors & Multivibrators

9.1 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.

9.2 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]

9.3 Checkoff Sheet

See Table 9.3 *Switching Transistors & Multivibrators Check-Off Sheet* on Page 96.

9.4 Switching Transistors

9.4.1 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

9.4.2 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.

9.4.3 Overdrive Switching

1. Design a switching circuit using a 2N3904 transistor with an $1\text{K}\Omega$ 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.

9.4.4 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 $1\text{K}\Omega$ 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.

9.5 Bipolar Junction Transistor Multivibrators

9.5.1 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.

9.5.2 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.

9.5.3 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.

9.5.4 Extreme Duty Cycle Astable Multivibrator

1. Create a schematic that connects the Astable circuit from Section 9.5.2 to the Monostable circuit from Section 9.5.3. 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.

9.6 Schmitt Trigger Inverter Astable Multivibrator

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.

9.7 555 Timer Multivibrators

9.7.1 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 9.5.1.
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.

9.7.2 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 9.7.1 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.

9.8 Monostable Multivibrators Integrated Circuits

9.8.1 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 $5\mu\text{s}$ 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.

9.9 Collected Data

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

9.10 Key Terms

Define The Following:

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

9.11 Key Formulas

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

9.12 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.

9.13 Table Formatting and Data Sets

Table 9.1: Switching Transistors (Section 9.4).

Section.9.4.2	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
<i>Specification</i>						
<i>Measured</i>						
Section.9.4.3	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
<i>Saturation_{Meas.}</i>						
<i>2xOD_{Meas.}</i>						
<i>4xOD_{Meas.}</i>						
Section.9.4.4	t_{delay}	t_{rise}	t_{on}	t_{fall}	$t_{storage}$	t_{off}
<i>Measured_{ComCap}</i>						

Table 9.2: 2N3904 Astable Multivibrators Data (Section 9.5).

Section.9.5.1	<i>PRF</i>	<i>PW</i>	<i>PS</i>	<i>DC</i>	<i>t_{rise}</i>	<i>t_{fall}</i>	<i>V_{OH}</i>	<i>V_{OL}</i>
<i>Calculated</i>								
<i>Measured</i>								
Section.9.5.2	<i>PRF</i>	<i>PW</i>	<i>PS</i>	<i>DC</i>	<i>t_{rise}</i>	<i>t_{fall}</i>	<i>V_{OH}</i>	<i>V_{OL}</i>
<i>Measured</i>								
Section.9.5.4	<i>PRF</i>	<i>PW</i>	<i>PS</i>	<i>DC</i>	<i>t_{rise}</i>	<i>t_{fall}</i>	<i>V_{OH}</i>	<i>V_{OL}</i>
<i>Calculated</i>								
<i>Measured</i>								

Table 9.3: Switching Transistors & Multivibrators Check-Off Sheet

<p>RCET 2252</p> <p>Clinical Assistant Professor</p> <p>Timothy Leishman</p> <p><i>Switching Transistors & Multivibrators</i></p> <p>Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>Switching Transistors</i>	9.4		
<i>Bipolar Junction Transistor Multivibrators</i>	9.5		
<i>Schmitt Trigger Inverter Astable Multivibrator</i>	9.6		
<i>555 Timer Multivibrators</i>	9.7		
<i>Monostable Multivibrators Integrated Circuits</i>	9.8		
Instructor Notes:			

Lab 10

Linear Regulators & Switching Power Supplies

10.1 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.

10.2 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]

10.3 Checkoff Sheet:

See Table 10.3 *Linear Regulators & SMPS Check-Off Sheet* on Page 108.

10.4 LM317 Linear Regulators

10.4.1 LM317 Specifications and Features

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

10.4.2 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 $1\text{K}\Omega$ 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.

10.4.3 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.

10.4.4 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.

10.4.5 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.

10.4.6 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.

10.5 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.

10.6 Unregulated Discrete Switch Mode Power Supply BUCK Design

10.6.1 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 10.1. 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 10.2. Make $VCC = 40V$.
5. Verify that the IRF9Z24N is functioning as a switch.

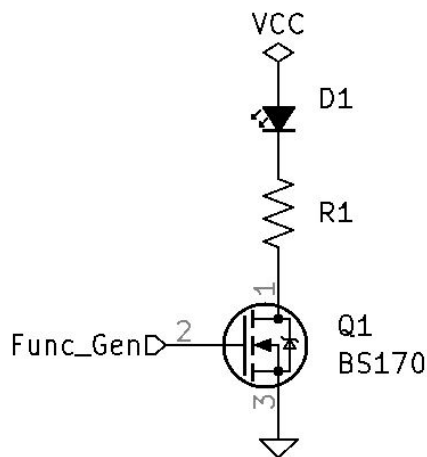


Figure 10.1: Switch Test Circuit 1

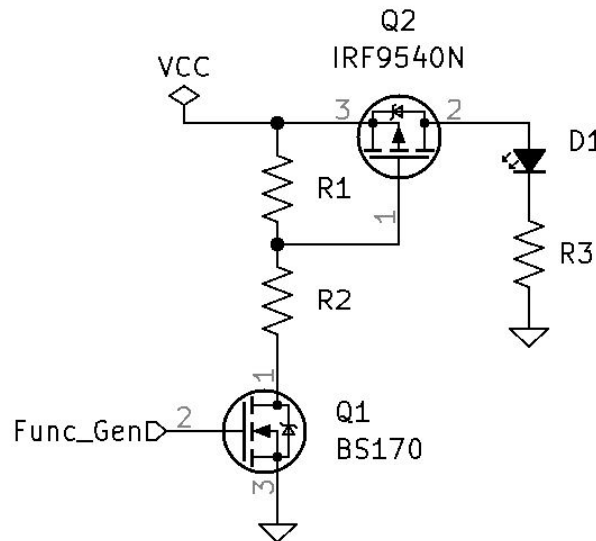


Figure 10.2: Switch Test Circuit 2

10.6.2 Inductor & Capacitor Calculations

1. See *SMPS BUCK Discrete Circuit* Figure 10.3.
2. Make VCC equal to $40V$ & IRL_{MAX} equal to 1 amp.
3. Show all calculations for $L1$.
4. Show all calculations for $C1$.

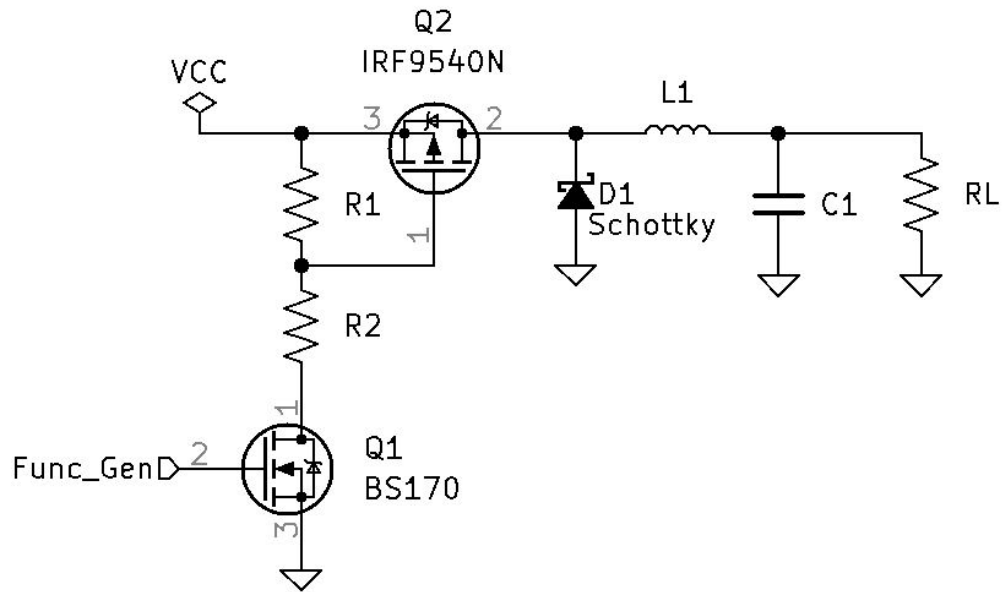


Figure 10.3: SMPS BUCK Discrete Circuit

10.6.3 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 $R_L = 10K\Omega$, $1K\Omega$, and 100Ω , see Table 10.1.
2. Minimize output ripple voltage by optimizing $C1$ for the circuit, see Table 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.

10.7 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 cycle		4	4.5	V
Input sink current (FEEDBACK)	V (FEEDBACK) = 0.7 V	0.3	0.7		mA

Figure 10.4: 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 10.3 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.

10.8 SMPS IC MC34063ACN

10.8.1 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 $T_A = 25^\circ C$	for DIP-8	1.25	W
		for SO-8	0.625	
T_J	Operating junction temperature		150	$^\circ C$
T_{STG}	Storage temperature range		-40 to 150	$^\circ C$
T_{OP}	Operating ambient temperature range	for AC and EC series	0 to 70	$^\circ C$
		for AB series	-40 to 85	
		for EB series	-40 to 125	

Figure 10.5: 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 $\approx 80\%$ efficient, and max power of the DIP-8 is $\approx 1W$. 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.

10.8.2 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.

10.8.3 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.

10.9 Collected Data

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

10.10 Key Terms

Define The Following:

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

10.11 Key Formulas

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

10.12 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.

10.13 Table Formatting and Data Sets

Table 10.1: Duty Cycle Testing (Section 10.6.3).

RL=10K Ω , C1=22 μ F	10%DC	20%DC	30%DC	40%DC	50%DC	$V_{ppRipple}$
<i>Measured V_{OUT}</i>						
RL=1K Ω , C1=22 μ F	10%DC	20%DC	30%DC	40%DC	50%DC	$V_{ppRipple}$
<i>Measured V_{OUT}</i>						
RL=100 Ω , C1=22 μ F	10%DC	20%DC	30%DC	40%DC	50%DC	$V_{ppRipple}$
<i>Measured V_{OUT}</i>						

Table 10.2: Load Testing (Section 10.6.3).

RL=25 Ω , C1=22 μ F	DutyCycle	$V_{ppRipple}$	%Ripple
$V_{OUT}=25V_{DC}$			
RL=25 Ω , C1=220 μ F	DutyCycle	$V_{ppRipple}$	%Ripple
$V_{OUT}=25V_{DC}$			
RL=25 Ω , C1=470 μ F	DutyCycle	$V_{ppRipple}$	%Ripple
$V_{OUT}=25V_{DC}$			

Table 10.3: Linear Regulators & SMPS Check-Off Sheet

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>Linear Regulators & SMPS</i> Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>Linear Regulation Fixed Voltage</i>	10.4.2		
<i>Linear Regulation Variable Voltage</i>	10.4.3		
<i>Linear Regulation Fixed Current</i>	10.4.4		
<i>Linear Regulation Variable Current</i>	10.4.5		
<i>Heat Sink Verification</i>	10.5		
<i>Unregulated Discrete SMPS</i>	10.6.3		
<i>Regulated Discrete SMPS</i>	10.7		
<i>MC34063 Buck</i>	10.8.1		
<i>MC34063 Boost</i>	10.8.2		
<i>MC34063 Inverter</i>	10.8.3		
Instructor Notes:			

Lab 11

DC Motors, Solenoids, and Servos

11.1 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.

11.2 Reference Documents:

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

11.3 Checkoff Sheet:

See Table 11.3 *DC Motors, Solenoids, and Servos Check-Off Sheet* on Page 117.

11.4 Lab Instructions:

11.5 DC Motors (Brushed)

11.5.1 DC Brushed Motor theory of operation

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

11.5.2 DC Motor Verification & Initial Testing

Verify DC Motor Operation Steps:

1. DC Voltage
2. Required Current
3. RPM
4. Document measured values. See Table 11.1 DC Motor Verification & Initial Testing (Section 11.5.2).
5. Repeat the previous steps while decreasing VDC by 10% for each iteration.

11.5.3 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 11.2 Switch Operation and PWM Speed Control (Section 11.5.3).

11.5.4 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.

11.5.5 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.

11.5.6 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.

11.5.7 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.

11.6 Solenoid

11.6.1 Solenoid Theory of Operation

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

11.6.2 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, $\approx 1\text{second}$, 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.

11.7 Servo

11.7.1 Servo Theory of Operation

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

11.7.2 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.

11.8 Electronic Speed Control (ESC)

11.8.1 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.

11.8.2 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.

11.9 Collected Data

- See *Table Formatting and Data Sets Examples* on page 114.
- Include all the data sets referenced in the lab.

11.10 Key Terms

Define The Following:

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

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: DC Motor Verification & Initial Testing (Section 11.5.2).

Section.11.5.2	<i>VDC</i>	<i>Current</i>	<i>RPM</i>
<i>100%</i>			
<i>90%</i>			
<i>80%</i>			
<i>70%</i>			
<i>60%</i>			
<i>50%</i>			
<i>40%</i>			
<i>30%</i>			
<i>20%</i>			
<i>10%</i>			

Table 11.2: Switch Operation and PWM Speed Control (Section 11.5.3).

Section.11.5.3	<i>Frequency</i>	<i>Time_{ON}</i>	<i>Current</i>	<i>RPM</i>
<i>99% Duty Cycle</i>				
<i>90% Duty Cycle</i>				
<i>80% Duty Cycle</i>				
<i>70% Duty Cycle</i>				
<i>60% Duty Cycle</i>				
<i>50% Duty Cycle</i>				
<i>40% Duty Cycle</i>				
<i>30% Duty Cycle</i>				
<i>20% Duty Cycle</i>				
<i>10% Duty Cycle</i>				

Table 11.3: DC Motors, Solenoids, and Servos Check-Off Sheet

RCET 2252 Clinical Assistant Professor Timothy Leishman			
<i>DC Motors, Solenoids, and Servos</i> Check-Off Sheet			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>DC Motor</i>	11.5.7		
<i>Solenoid</i>	11.6.2		
<i>Servo</i>	11.7.2		
<i>ESC Brushed DC Motor</i>	11.8.1		
<i>ESC Brushless DC Motor</i>	11.8.2		
Instructor Notes:			

Lab 12

Stepper Motors

12.1 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.

12.2 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]

12.3 Checkoff Sheet:

See Table 12.3 *Stepper Motors Check-Off Sheet* on Page 125.

12.4 Stepper Motor Control Circuitry

12.4.1 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.

12.4.2 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 $\approx 20\text{Hz}$.
 - (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.

12.4.3 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 12.4.2).
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.

12.4.4 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 12.4.2).
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.

12.4.5 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 12.4.2).
 - (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.

12.4.6 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 12.4.2.
- (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.

12.5 Collected Data

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

12.6 Key Terms

Define The Following:

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

12.7 Key Formulas

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

12.8 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.

12.9 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.

12.10 Table Formatting and Data Sets

Table 12.1: 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
<i>SN74194 Predicted</i>					
<i>SN74194 Measured</i>					
<i>JK FF Predicted</i>					
<i>JK FF Measured</i>					
<i>A4988 Predicted</i>					
<i>A4988 Measured</i>					
<i>TMC2208 Predicted</i>					
<i>TMC2208 Measured</i>					

Table 12.2: Stepper Motor Circuit measured RPM and Clock Frequency

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

Table 12.3: 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	12.4.2		
JK Flip Flop Whole Step with Direction Control	12.4.3		
JK Flip Flop Half Step with Direction Control	12.4.4		
A4988 Stepper Motor Driver	12.4.5		
TMC2208 Stepper Motor Driver	12.4.6		
Instructor Notes:			

Lab 13

LabVIEW Integration

13.1 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.

13.2 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

13.3 Checkoff Sheet:

See Table 13.1 *LabVIEW Integration Check-Off Sheet* on Page 130.

13.4 LabVIEW Motor Control Integration

Develop a single LabVIEW program to provide a Graphical User Interface (GUI) that meets the following requirements.

13.4.1 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.

13.4.2 Solenoid

1. The LabVIEW GUI will allow the user to activate a Solenoid in a bidirectional motion.
2. The LabVIEW program will control an activation time of 1 second.
3. The LabVIEW GUI will indicate when the Solenoid is active and the direction of motion.

13.4.3 Servo

1. The LabVIEW program and GUI will provide two-position control of a servo motor.
2. The LabVIEW GUI will provide a visual representation of the servo position.

13.4.4 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.

13.5 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.

13.6 Key Terms

Define The Following:

- LabVIEW
- GUI

13.7 Troubleshooting Procedure

- Develop a step-by-step troubleshooting procedure for a LabVIEW integrated system.

13.8 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.

13.9 Table Formatting and Data Sets

Table 13.1: LabVIEW Integration Check-Off Sheet

<p style="text-align: center;">RCET 2252 Clinical Assistant Professor Timothy Leishman</p> <p style="text-align: center;"><i>LabVIEW Integration</i> Check-Off Sheet</p>			
Student Name:		Lab Start Date:	
Check-Off	Section	Date	Instructor Int.
<i>DC Motor: GUI and Speed Control</i>	13.4.1		
<i>DC Motor: Direction and Emergency Stop</i>	13.4.1		
<i>DC Motor: RPM, Closed Loop or Open Loop Control</i>	13.4.1		
<i>Solenoid: GUI, 1 Sec, Direction Control</i>	13.4.2		
<i>Servo: GUI, Two Position Control</i>	13.4.3		
<i>Stepper Part A: GUI, Resolution, Speed (RPM), Direction</i>	13.4.4		
<i>Stepper Part B: 180° position control</i>	13.4.4		
Instructor Notes:			

References

- [1] Tektronix, “Tektronix xyzs of oscilloscopes.” https://download.tek.com/document/03W_8605_7_HR_Letter.pdf. (accessed Sept. 18, 2023).
- [2] “Tektronix tds user manual.” https://download.tek.com/manual/071273300web_0.pdf. Accessed: 2023-09-18.
- [3] “Tektronix afg1022 user manual.” <https://download.tek.com/manual/AFG1022-Quick-Start-User-Manual-EN.pdf>. Accessed: 2023-09-18.
- [4] “Power supply gps4303 user manual.” <https://www.gwinstek.com/en-global/products/downloadSeriesDownNew/8083/1210>. Accessed: 2023-09-18.
- [5] “Get more from your basic oscilloscope with the fft function.” <https://www.tek.com/en/blog/get-more-your-basic-oscilloscope-fft-function>. Accessed: 2023-09-18.
- [6] *Solid State Pulse Circuits 4Th Ed.* Prentice-Hall Of India Pvt. Limited, 2006.
- [7] “Multi-stage amplifier schematic.” https://docs.google.com/viewer?url=https://github.com/leistimo/RCET_ThirdSemester/raw/master/RCET2253/MultiStageAmp/MultiStageSchematic.pdf. Accessed: 2023-09-26.
- [8] “Multi-stage amplifier pcb layout.” https://docs.google.com/viewer?url=https://github.com/leistimo/RCET_ThirdSemester/raw/master/RCET2253/MultiStageAmp/MultiStageLayout.pdf. Accessed: 2023-09-26.
- [9] “Tl071 data sheet.” <http://www.ti.com/general/docs/suppproductinfo.tsp?distId=10&gotoUrl=http%3A%2F%2Fwww.ti.com%2Flit%2Fgpn%2Ftl071>. Accessed: 2023-10-25.
- [10] “Mcp6002 data sheet.” <https://ww1.microchip.com/downloads/en/DeviceDoc/MCP6001-1R-1U-2-4-1-MHz-Low-Power-Op-Amp-DS20001733L.pdf>. Accessed: 2023-10-25.
- [11] “Lm741 data sheet.” https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/1172/LM741_Series_Rev_July_2016.pdf. Accessed: 2023-10-25.
- [12] “2n3904 data sheet.” <https://www.onsemi.com/pdf/datasheet/pzt3904-d.pdf>. Accessed: 2023-11-01.

- [13] “Lm555 data sheet.” <https://www.ti.com/general/docs/suppproductinfo.tsp?distId=10&gotoUrl=https%3A%2F%2Fwww.ti.com%2Flit%2Fgpn%2Flm555>. Accessed: 2023-11-01.
- [14] “Sn7414 data sheet.” <https://www.ti.com/lit/ds/symlink/sn74hc14.pdf?ts=1638587495517>. Accessed: 2023-11-01.
- [15] “Sn74121 data sheet.” <https://www.ti.com/general/docs/suppproductinfo.tsp?distId=10&gotoUrl=https%3A%2F%2Fwww.ti.com%2Flit%2Fgpn%2Fsn74121>. Accessed: 2023-11-01.
- [16] “Bu4538b data sheet.” <https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/909/bu4538b.pdf>. Accessed: 2023-11-01.
- [17] “Lm317 data sheet.” <https://www.st.com/content/ccc/resource/technical/document/datasheet/group1/a0/db/e6/9b/6f/9c/45/7b/CD00000455/files/CD00000455.pdf/jcr:content/translations/en.CD00000455.pdf>. Accessed: 2023-11-01.
- [18] “Heatsink hse20635035 hw data sheet.” <https://www.cuidevices.com/product/resource/hse-bx-035h-01.pdf>. Accessed: 2023-11-01.
- [19] “Bs170 data sheet.” <https://rocelec.widen.net/view/pdf/fonxoqycul/FAIRS29185-1.pdf?t.download=true&u=5oefqw>. Accessed: 2023-11-06.
- [20] “Irf9z24n data sheet.” <https://www.infineon.com/dgdl/irf9z24npbf.pdf?fileId=5546d462533600a40153561218961ddb>. Accessed: 2023-11-06.
- [21] “Tl494 data sheet.” <https://www.ti.com/general/docs/suppproductinfo.tsp?distId=10&gotoUrl=https%3A%2F%2Fwww.ti.com%2Flit%2Fgpn%2Ftl494>. Accessed: 2023-11-06.
- [22] “Designing switching voltage regulators with the tl494.” <https://www.ti.com/lit/pdf/slva001>. Accessed: 2023-11-15.
- [23] “Mc34063acn data sheet.” <https://www.st.com/content/ccc/resource/technical/document/datasheet/03/f9/c4/3d/7f/eb/4c/5e/CD00001232.pdf/files/CD00001232.pdf/jcr:content/translations/en.CD00001232.pdf>. Accessed: 2023-11-06.
- [24] “74194 shift register data sheet.” <https://rocelec.widen.net/view/pdf/burr0qfj4i/NATLS14092-1.pdf?t.download=true&u=5oefqw>. Accessed: 2023-11-27.
- [25] “Jk flip flop data sheet.” <https://www.ti.com/general/docs/suppproductinfo.tsp?distId=10&gotoUrl=https%3A%2F%2Fwww.ti.com%2Flit%2Fgpn%2Fcd74hc112>. Accessed: 2023-11-27.
- [26] “17hs13-0316s stepper motor data sheet.” <https://www.omc-stepperonline.com/download/17HS13-0316S.pdf>. Accessed: 2023-11-27.

-
- [27] “Pololu a4988 stepper driver data sheet.” <https://www.pololu.com/product-info-merged/2980>. Accessed: 2023-11-27.
- [28] “Tmc2208 stepper driver data sheet.” https://www.mouser.com/datasheet/2/609/TMC2202_TMC2208_TMC2224_datasheet_rev1_13-3364648.pdf. Accessed: 2023-11-27.