Year 2 Project

Proving chaos in a simple RLD circuit by comparison with a series RLC resonant circuit

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Supervised by: Steve Hall

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Abstract

Chaos has applications in many different fields, and as such it is important to be able to cheaply and easily build a chaos circuit, in order to spend more money and time on extended research. This paper shows that it is possible to achieve a chaotic output using only 3 circuit components, by comparing and RLD circuit to a series RLC resonance circuit. The non-lineartiy in the diode of the RLD circuit is sufficient to create chaos, as long as the right component values are used. This means extended research can more reliably be carried out as there are less parameters required to be kept consistent in the initial chaos circuit.

Declaration

I confirm that I have read and understood the University's definitions of plagiarism and collusion from the Code of Practice on Assessment. I confirm that I have neither committed plagiarism in the completion of this work nor have I colluded with any other party in the preparation and production of this work. The work presented here is my own and in my own words except where I have clearly indicated and acknowledged that I have quoted or used figures from published or unpublished sources (including the web). I understand the consequences of engaging in plagiarism and collusion as described in the Code of Practice on Assessment (Appendix L).

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Chapter 1

Introduction

1.1 Introduction

Chaos is a phenomenon very similar to randomness, where the outcome is very difficult to predict because of the extreme sensitivity to initial parameters. However, chaos and randomness are not the same. Randomness means no part of a system determines any other part, whereas chaos is, as Edward Lorenz summarises it [1], “when the present determies the future, but the approximate present does not approximately determine the future.”

There are many real world applications for chaos, including modeling weather and climate, modelling road traffic and encryption. Chaos circuits could also be used in biology and medicine, such as in pacemakers to create more natural heartbeats [2]. As such, being able to make a simple circuit with chaotic behaviour, not only makes these applications easier, as there are less variables to control, but also allows for cheaper implementation as the components required are simple and not needed in large amounts.

Chua’s circuit is a simple electronic circuit which shows this chaotic behaviour. Using just one non-linear component it is extremely cheap, and can be very physically small to implement. Chua’s circuit is a nonperiodic oscillator, and as such, produces chaos as a waveform. The standard Chua’s circuit is composed of a resistor, an inductor, two capacitors and a Chua’s diode. Though a simpler version of the circuit exists which consists of a resistor, inductor and regular diode, which is what is be used in this lab project.

This lab project consists of building a simple series resistor, inductor, diode (RLD) Chua’s circuit, and comparing it to a series resistor, inductor, capacitor (RLC) resonance circuit in order to confirm that chaos can be achieved with few and simple components.

1.2 Objectives

1 Develop a series RLC resonance circuit and show chaos is not produced

2 Develop a series RLD chua chaos circuit and show chaos is produced

3 Compare the RLC and RLD circuits to prove the RLD circuit can produce chaotic signals and show the difference between chaotic and non-chaotic outputs.

Chapter 2

Materials and Methods

2.1 Materials

- Tektronix AFG1022 Arbitrary Function Generator
- Tektronix TDS 1012B Two Channel Digital Storage Oscilloscope
- Hewlett-Packard 4274A Multi-Frequency LCR Meter
- 220 Ohm resistor ± 5% (Measured 215.96 Ohms)
- 2x 22mH Inductor ± 10% (Measured 23.31mH and 23.03mH)
- 70pF Capacitor ± 10% (Measured 68.5pF)
- 10pF Capacitor ± 10% (Measured 10.9pF)
- 1n4007 diode (Measured 81.29pF reverse capacitance)
- PSPICE Student Edition 9.1

2.2 Method/Procedure

2.2.1 PSPICE frequency sweep on an RLC circuit:

Using PSPICE, a frequency sweep was performed on the RLC circuit, with actual component values as shown in Figure 2.1. Figure 2.1 uses combined component values for simplification of the simulation. The resistor, R1, includes the deliberate resistance value of 215.96 Ohms, and the internal resistance of the two inductors, measured to be 40.00 Ohms each. Capacitor C1 is a parallel combination of the two real capacitors, and the inductor L1 is a series combination of the two inductors.

2.2.2 Voltage sweep of a real RLC circuit:

The RLC circuit was built as per Figure 2.2, and the voltage across the resistor measured against the input voltage of the circuit by setting the oscilloscope to X-Y mode. The input frequency of the circuit was set to the resonant frequency of 82kHz (Figure 3.1), and a voltage sweep performed between 0 and 20V input. A Fast Fourier Transform was also taken at 15V.

2.2.3 PSPICE frequency sweep on an RLD circuit:

A frequency sweep of the RLD circuit in figure 2.3 was performed in PSPICE, using the same parameters that the RLC circuit was swept with. The capacitance value of the diode D1 was set to the capacitance used for the RLC circuit, 81.3pF.

2.2.4 Voltage sweep of a real RLD circuit:

The RLD circuit was built as per Figure 2.4, and the voltage across the resistor measured against the input voltage of the circuit by setting the oscilloscope to X-Y mode. The input frequency of the circuit was set to the resonant frequency of 81.3kHz (Figure 3.4), and a voltage sweep performed between 0 and 20V input. A Fast Fourier Transform was also taken at 15V.

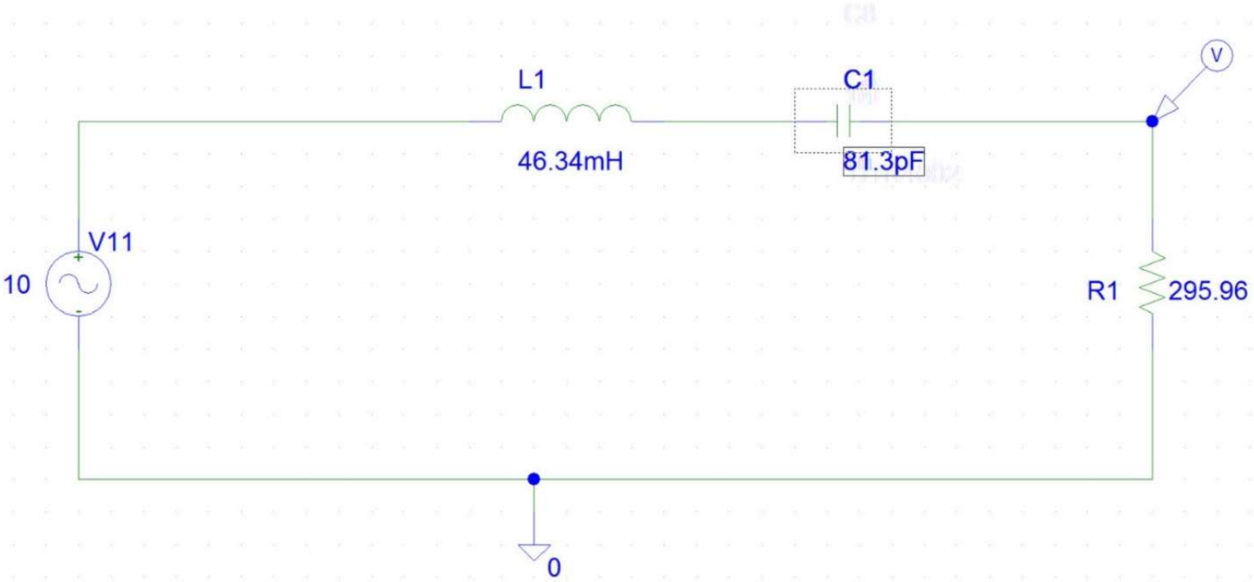


Figure 2.1. PSPICE diagram for an RLC circuit, using actual component values.

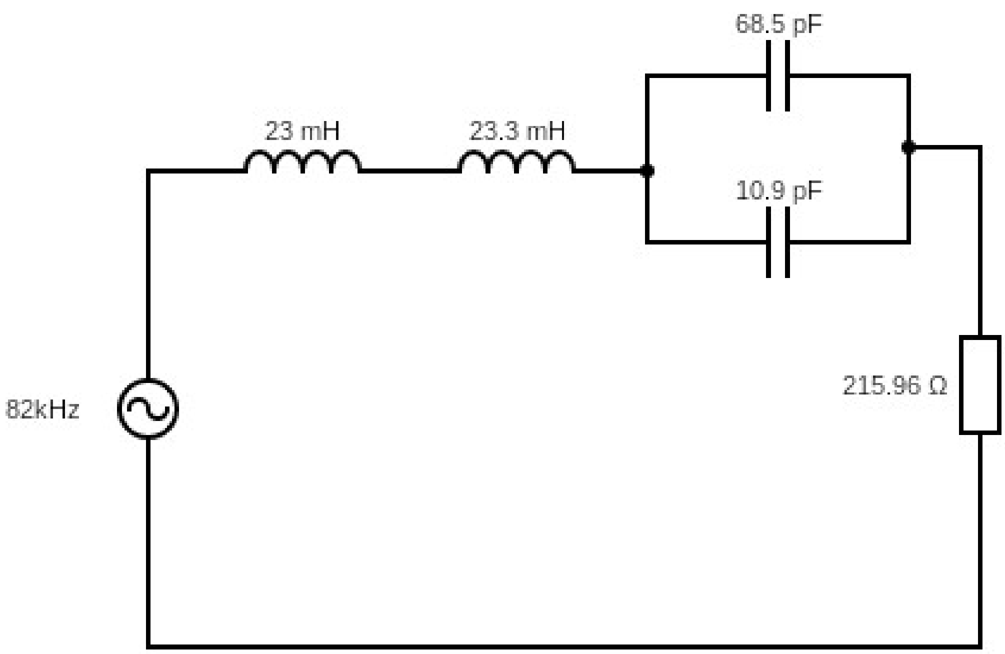


Figure 2.2. Actual RLC circuit layout

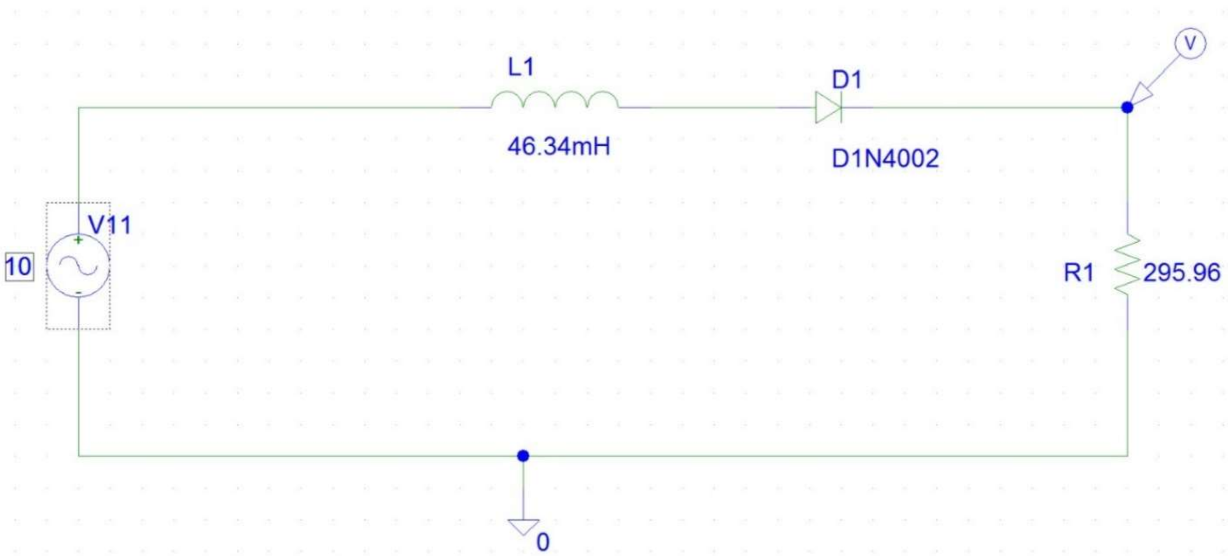


Figure 2.3. PSPICE diagram for an RLD circuit, using actual component values.

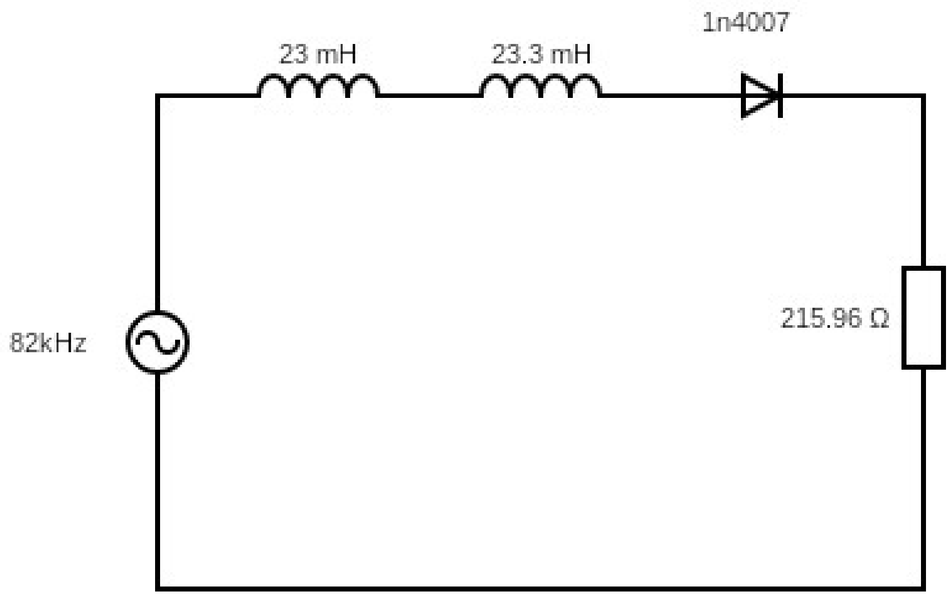


Figure 2.4. Actual RLD circuit layout

Chapter 3

Results

3.1 Results of the PSPICE frequency sweep on an RLC circuit

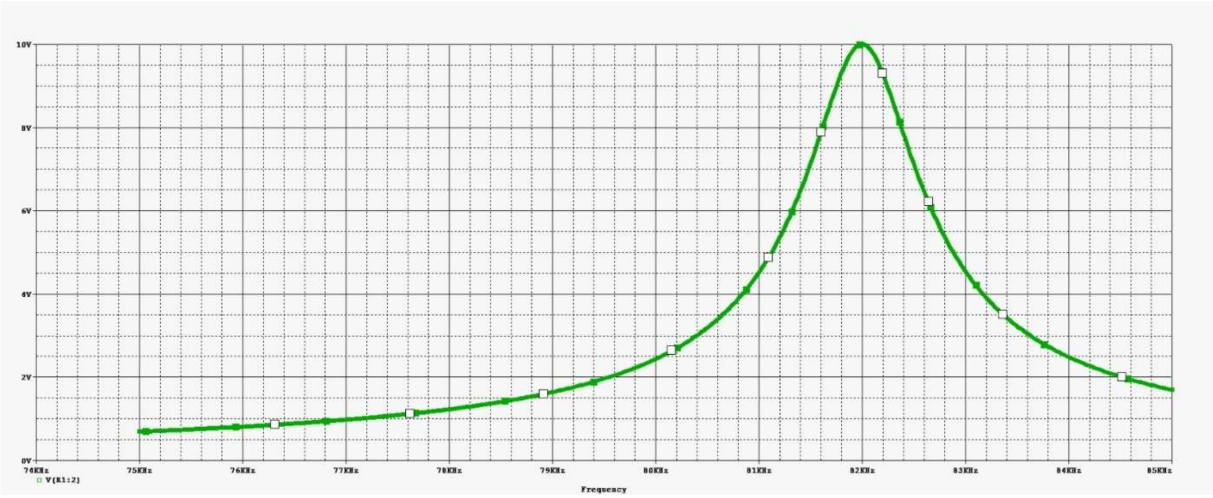


Figure 3.1. Frequency sweep of an RLC circuit in PSPICE

The graph Figure 3.1 shows the response of the circuit to a wide range of input frequencuies. The graph shows the peak at 82kHz.

The theoretical value is calculated by usiong the euqation

$$f = \frac{1}{2\pi\sqrt{L \times C}}$$

Therefore, the theoretical value is:

$$f = \frac{1}{2\pi\sqrt{43.34m \ \times 81.3p}}$$

$$f = 82kHz$$

The theoretical and simulation values are the same, which is expected for the simple RLC resonance circuit.

3.2 Results of the Voltage sweep of a real RLC circuit

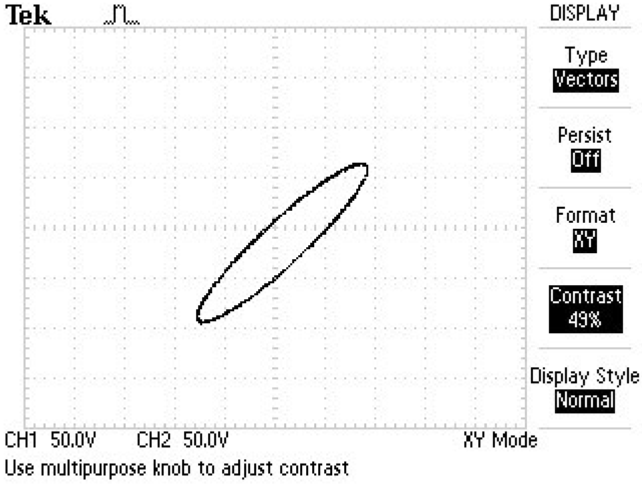


Figure 3.2. Resistor Voltage vs Input Voltage at 15V

Figure 3.2 shows the voltage response of a resonant frequency input to the circuit. Only one ring is observed in the RLC circuit, as the circuit has no non-linear components and as such, will always have a defined relationship between input and output.

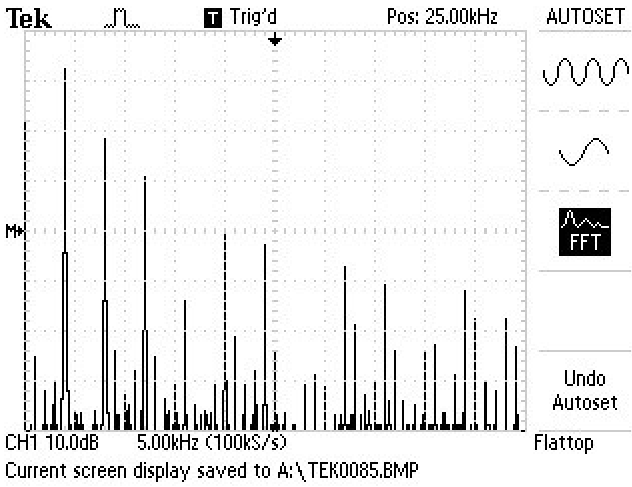


Figure 3.3. Fast Fourier Transform of Figure 3.2

Figure 3.3 shows a fast fourier transform of the single ring in Figure 3.2. Figure 3.3 has peaks at each harmonic of the resonant frequency, all multiples of 82kHz. This is normal harmonic behaviour and is as expected for the simple RLC circuit.

3.3 Results of the PSPICE frequency sweep on an RLD circuit

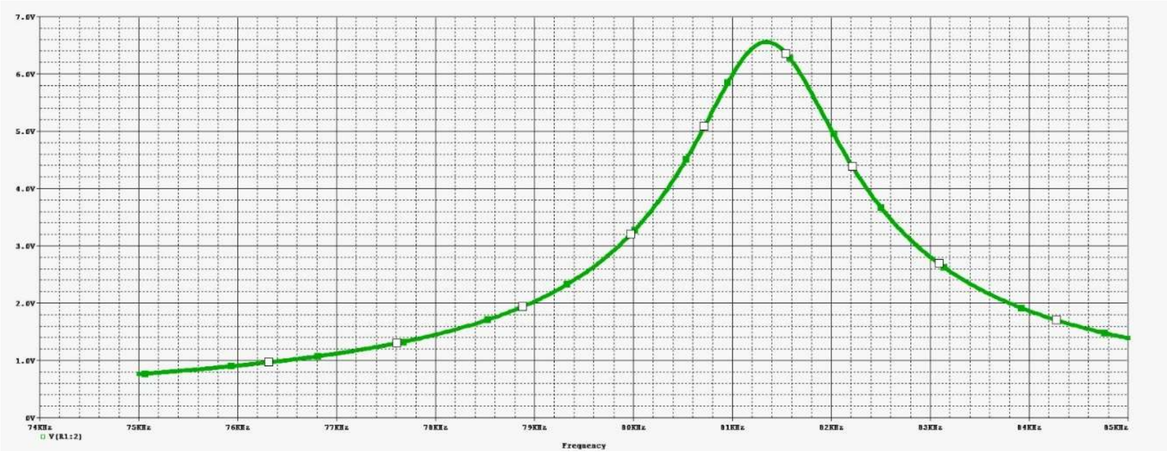


Figure 3.4. Frequency sweep of an RLD circuit in PSPICE

The graph Figure 3.4 shows the response of the diode circuit to a wide range of input frequencuies. The graph shows the peak at 81.3kHz.

The theoretical value is calculated by usiong the euqation

$$f = \frac{1}{2\pi\sqrt{L \times C}}$$

Therefore, the theoretical value is:

$$f = \frac{1}{2\pi\sqrt{43.34m \ \times 81.3p}}$$

$$f = 82kHz$$

The simulated value is within 1kHz of the calculated value, which means it is withing the range of expected values. This difference is due to the diode having a slightly smaller measured capacitance, at 81.29pF, rather than 81.3pF.

3.4 Results of the Voltage sweep of a real RLD circuit

Table 3.1. Threshold voltages for numbers of rings observed in an RLD circuit

Voltage/V ± 0.05V	**Number of rings observed**	**Appendix figure associated**
0.0 – 2.4	1	C.1
2.4 – 2.8	2	C.2
2.8 - 3.3	3	C.3
3.3 - 5.4	2	C.4
5.4 – 6.0	4	C.5
6.0 – 6.5	chaos	C.6
6.5 – 6.6	4	C.7
6.6 – 7.7	chaos	C.8
7.7 – 10.1	3	C.9
10.1 – 10.8	6	C.10
10.8 – 17.8	chaos	C.11
17.8 – 20.0	4	C.12
20.0	chaos	C.13

Table 3.1 shows the ranges of voltage inputs needed to observe different numbers of rings on the oscilloscope when using the RLD circuit. The ranges overlap as the exact point where the number of circles changes is not a single point. Observing chaotic results on the oscilloscope, like at 6.0V, is one of the two signs of the desired chaos in the system.

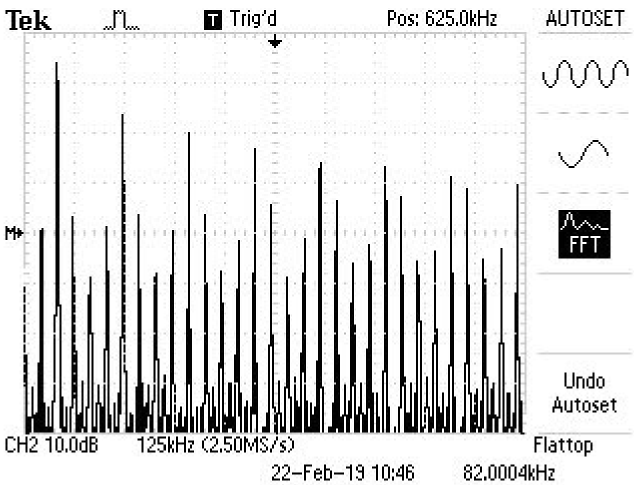


Figure 3.5. Fast Fourier Transform of an RLD circuit at 15V

Figure 3.5 shows a fast fourier transform of the RLC circuit at 15V input voltage. What is different here to the RLC fast fourier transform, is the fact that peaks are observed not only on harmonics of the resonant frequency, but also on half and quarter harmonics. As seen in the Figure, there are 2 half peaks and a quarter peak between every harmonic peak. This is known as bifurcation, and is the second phenomenon associated with a chaotic system.

Chapter 4

Discussion and Conclusions

4.1 Explanation of results

Figure 3.1 shows the frequency sweep of the RLC circuit, and shows the resonant frequency lies at 82kHz for the component values used. The resonant frequency of the circuit is the frequency at which the complex components of the impedence of the inductor and capacitor in the circuit cancel one another out, so the resulting amplitude reaches its maximum. This is the frequency desired to be used for real circuit tests, as chaos happens only around the resonant point for a circuit, so in order to properly compare a chaotic and non-chaotic circuit, the resoant points for both must be known and similar.

Figure 3.2 shows the results of plotting the input voltage against the voltage across the resistor in the RLC circuit. Only one oscilloscope image is shows as the RLC circuit exhibited no chaotic behaviour, so manipulation of the input voltage on changed the size of the resulting ring, and did not produce more.

Figure 3.3 shows the fast fourier transform of figure 3.2, and shows the standard resonant fourier transform, with peaks at each of the harmonics of the resonant frequency used (82k, 164k, 246k, etc..). It is important to obtain both a single ring as in Figure 3.2 and a standard harmonic fourier transform as in Figure 3.3, as these explicity show that the circuit is not chaotic, so when comparing against the RLD circuit, any chaotic behaviour is easily noticable. These findings also support objective 1, as a series RLC circuit has been developed, and does not produce chaos.

Figure 3.4 shows the frequency sweep simulation of the RLD circuit, and shows the resonant frequency to be between 81.2kHz, and 81.4kHz. This is small difference in resonant frequency between RLC and RLD simulation is due to the reverse bias capacitance of the diode, which was set to 81.29pF, as opposed to 81.3pF. However, the difference is small enough that it will be made up for by floating capacitance in the real circuit, and as such the calculated resonant peak of 82kHz should be used in the actual testing.

Table 3.1 shows the results of testing the RLD circuit with a resonant input, and changing the voltage. Obtaining an increasing number of rings with increasing voltage is a sign that a system is chaotic, and images of these different numbers of rings produced can be seen in Appendix A, in figures C.1 to C.13. Comparing these chaning numbers of rings to the single, static ring seen in the RLC circuit shows that the RLD circuit does indeed produce a chaotic signal.

Figure 3.5 shows an example of a fast fourier transform of a chaotic ring, and when comparing to the Figure 3.3, it can easily be seen that the RLD circuit also produces smaller peaks along the half and quarter harmonics as well as the large peaks on each harmonic. This is the frequency bifurcation and is also an effect of a chaotic system, as such it is a second piece of evidence that the RLD circuit is produces a chaotic output.

Both the results from Table 3.1 and Figure 3.5 complete objective 2, as a series RLD circuit has been prodcued, and shown to produce a chaotic output. Having two forms of evidence that the RLD circuit causes chaos proves that the circuit, is in fact chaotic, and should be able to be used for any application that requires a chaotic circuit, as long as it is set up with the correct values. The comparison between the results of an RLC resonance circuit and the results of the RLD circuit also clearly show the difference between chaotic and non-chaotic outputs, which fulfills objective 3 of this project.

4.2 Self evalulation

The project realised its goals, however the prject itself could have gone better. There were initial complications in the project due to not properly being able to measure the capacitance of a diode, and had those complications not occurred, the project objectives could have been extended to testing and proving a more complicated chaos circuit to show that the same chaos result is achieved between a simple 3 component RLD circuit, and a more complicated chua’s circuit.

The project was limited by the time allotted, and knowledge of chaos and chaos theory. Had there been more time, the project could have expanded into attempting to use the chaos circuits in a larger simulation to show their real world applications. If we were more well versed in the fields of chaos, the project also could have attempted to synchronise two chaotic circuits, in order to encrypt and decrypt information.

This project, however, remains useful to many, as it shows chaos can be easily and cheaply achieved, with only a single non-linear component, and two linear components. This means other projects can more quickly establish a chaotic circuit as their basis, and build on it further in more applied ways, such as the encryption and decryption mentioned earlier.

4.3 Recommended areas of further work

As this project was desinged to show a simple chaos circuit, recommended areas of further work would be those that require small chaotic devices, such as using chaos in medicine and biology, similar to the pacemaker mentioned in the introduction.

Encryption and decryption would also be a recommended area of further study, as with a simpler circuit, there are less parameters that are needed to be kept consistent across the synchronised circuits, and as such the maintaining of these circuits as a security device will be easier.

4.4 Conclusions

In conclusion, the series RLC circuit does not produce a chaotic output, as expected, whereas the RLD circuit does. The RLD circuit is simpler than most other chaos circuits, as it requires only 3 components, and as such can be made very small and very cheaply, so can be used effectively in every relevant area of study.

Chapter 5

Theory

5.1 Why an RLD causes chaos

The reason an RLD circuit causes chaos is due to the components it is comprised of, with the non-linearity in the diode being key. The diode causes these chaotic effects, as when the ac current flows through the system, the diode appears as an open circuit to the system in one direction, so there is no resonance, but in the other direction, the diode appears as a capacitor. As such, the circuit constantly flips between two states, appearing as an RL circuit in one direction, and an RLC resonant circuit in the other. This means the signal is constantly changing due to the different charge/discharge values of the capacitor every time the current direction switches. Because the value of this component is always chaning in the circuit, the output becomes chaotic.

References

[1] C Danforth, “Chaos in an Atmosphere Hanging on a Wall”, http://mpe.dimacs.rutgers.edu/2013/03/17/chaos-in-an-atmosphere-hanging-on-a-wall/, Mathematics of Planet Earth, April 2013, Accessed March 2019

[2] W Ditto, “Applications of chaos in biology and medicine”, AIP Conference proceedings 376, 175 (1996), https://doi.org/10.1063/1.51060, 12 May 2008, Accessed March 2019

Appendices

Appendix A

Role allocation/responsibility matrix

	Member Name	Title(s)
1	Yifan Wei	Project manager designer
2	Lochlainn	Technical Writer Designer
3	Tianjian Zhong	Developer Designer

Responsibility Matrix

KEY:

R – Responsible (accountable) for completion of task. (Task can be delegated to this person.)

S – Supports task.

C – Requires communication about the task.

Title	Project Activity				Deliverables			
	Requirements/ Scope	Design	Implementing	Testing	Poster	Blog	Bench	Report
Project Manager	R	C	S	S	S	S	S	S/R
Designer	C	R	S	S	S	S	S	S
Implementer/ Developer	C	S	R	S	C	C	R	S
Technical Writer	C	S	S	S	R	R	C	R

<u>Typical Roles</u>

Title	Role	Responsibilities
Project Manager	Responsible for developing, in conjunction with the supervisor, the project scope. The Project Manager ensures that the project is delivered on time and to the required standards.	• Managing and lead the project team. • Managing the coordination of the partners and the working groups.
Designer	Designing the system (the circuit, the code, etc.).	• Creating the required block diagrams, circuit diagrams, flow charts, etc.
Implementer/Developer	Implementing the suggested design	• Connecting the systems/circuit • Writing the code

Title	Role	Responsibilities
Technical Writer	Documenting the project progress and deliverables	• Recording and maintaining all meeting logs • Updating the logbook. • Creating project blog • Creating project poster • Writing project report
<Title>	<Role>	• <Responsibility>
<Title>	<Role>	• <Responsibility>
<Title>	<Role>	• <Responsibility>
<Title>	<Role>	• <Responsibility>

Contribution to project deliverables

	Member name	Deliverable(s)	Comments
1	YIFAN WEI	Poster, data collection and analyse, circuit develop, weekly report	Mainly focus on project task allocation and data analyse
2	LOCHLAINN	Blog, circuit simulation, weekly report, report	Mainly focus on the simulation of circuit and technic writing part
3	TIANJIAN ZHONG	Circuit develop, weekly report, poster	Mainly focus the manipulation of the circuit

Attendance Record

	Member name	Attended the weekly meeting? (Yes/No)					Comments
		Week 1	Week 2	Week 3	Week 4	Week 5	
1	YIFAN WEI	YES	YES	YES	YES	YES	
2	LOCHLAINN	YES	YES	YES	YES	YES	
3	TIANJIAN ZHONG	YES	YES	YES	YES	YES	

Supervisor weekly meeting log week 1

Date: 7 Feb Supervisor: S Hall

Project Title: Investigate a Chau chaos circuit (L, R, diode in series) – compare it to a linear L, C, R resonant circuit

Student Names /Attendees:	1.Yifan Wei	2. Tianjian Zhong
3. Lochlainn Hankin-Appleby		

Summary of week's activities: LCR Circuit simulated on PSPice with parameters of components available. LCR circuit breadboarded and tested against multiple frequencies and voltages. LDR circuit simulated on PSPice with same parameters as LCR circuit, and a 1n4001 diode. LDR circuit breadboarded and tested with same frequencies and voltages as LCR circuit.

Problem, issues and concerns: We could not reliably get multiple loops on the LDR output. We did not have specific values in mind for components or a desired resonant frequency.

Tasks for next week/Actions for next meeting: Come up with specific desired resonant frequency and do some circuit design to obtain values of components that should be used. Do some more research into chaos circuits to understand why and how chaos occurs in the LDR circuit, and obtain more than one loop when breadboarded.

Supervisor use only

Progress Assessment: □ Satisfactory **Comments/Recommendations: A good start. Yes – please log carefully all experimental detail; you want to be able to compare theory, simulation and expt. results. Important to find the information regarding signs of chaos. You have some clues with the Lissajou figures but there's another phenomenon you get with chaos… Hint: 'bifurcation'** **Supervisor Signature: S Hall**

Supervisor weekly meeting log week 2

Date: 14/2/2019 Supervisor: Professor S. Hall

Project Title: Investigate a Chau chaos circuit (L, R, diode in series) – compare it to a linear L, C, R resonant circuit

Student Names /Attendees:	1.Yifan Wei	2.Tianjian Zhong
3.Lochlainn Hankin-Appleby		

Summary of weeks activities:
Theoretical values of components were calculated to give a desired resonant frequency, and tested in PSPICE, which gave a resonant peak at the calculated value when given the calculated inputs. The value calculated and obtained was approximately 8.7 kHz. The LDR circuit was constructed using the calculated and simulated theoretical values, and tested against the resonant frequency of ~8.7 kHz This however, did not seem to agree, as we could not produce more than 1 loop using these values. At this resonant frequency, chaos would be expected, but it was not achieved.

Problem, issues and concerns:
We could not get the LDR circuit to produce more than one loop on the oscilloscope, and as such could not confirm chaos. It is possible one of the component readings was incorrect, and as such an incorrect resonant frequency calculated.

Tasks for next week/Actions for next meeting:
Include inductor resistance in the PSPICE simulation. Investigate bifurcation in the LDR circuit in order to further investigate chaos. Re-test component readings and ensure the calculations were done using the correct values. Obtain FFT views of any output where we expect to get either more than 1 loop, or obtain chaos, in order to better see what signal we are actually getting.

Supervisor use only

Progress Assessment □ Satisfactory
Comments/Recommendations: Quote exact theoretical, simulation and experimental values rather than say they are 'approximately the same.' Try to explain any differences.

Complete the blog so I can see actual results. Alternatively, you could have a log book with all the results – graphs circuit diagrams, pasted in. Supervisor Signature: SH

Supervisor weekly meeting log week 3

Date: 16/2/2019 Supervisor: Professor S. Hall

Project Title: Investigate a Chau chaos circuit (L, R, diode in series) – compare it to a linear L, C, R resonant circuit

Student Names /Attendees:	1.Yifan Wei	2.Tianjian Zhong
3.Lochlainn Hankin-Appleby	4.	5.

Summary of week's activities:
The new circuit be builded which is a 3rd order circuit. It composed by a 1KΩ linear resistance, a variable resistance (0- 1KΩ), a 14.57mH inductor, two capacitors (9.85nF and 100.3nF) and a Chua's non-linear resistance (composed by two amplifiers and six linear resistors). By replacing the diode with a more complex Chua's non-linear resistor, a clearer single ring phenomenon has been found. Chaos would be expected by using this circuit, but it was not achieved.

Problem, issues and concerns:
The input signal is a pure sine wave with 10Khz and 5V, the output signal should be a two or more peaks sine waves. After the test, some harmonics be found in FFT analysis, but the output signal is pure sine wave on the oscilloscope. Additionally, the double rings phenomenon and chaos is difficult to be found. The change of the linear resistance could not induce double turbination chaos attractor.

Tasks for next week/Actions for next meeting:
Discuss the problems in experiment, find out the correct test position in the circuit by using oscilloscope. Find some formulas on the Internet to calculate the required resistance of chaos, and build a new non-linear resistance with calculated values.

Use Matlab and PSPICE to simulate chaos phenomenon.

Supervisor use only

Progress Assessment: □ Unsatisfactory ☑ Satisfactory □ Good

Comments/Recommendations:

Supervisor Signature:

Supervisor weekly meeting log week 4

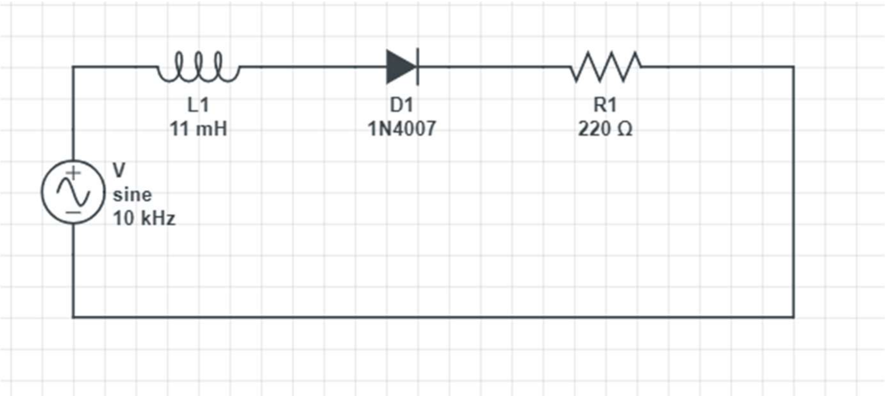
Date: 25 Feb Supervisor: S Hall

Project Title: Investigate a Chau chaos circuit (L, R, diode in series) – compare it to a linear L, C, R resonant circuit

Student Names /Attendees:	1. Yifan Wei	2. Lochlainn Hankin-Appleby
3. Tianjian Zhong		

Summary of week's activities:

We success get result of the RCL in series chaos circuit and test for different frequency and amplitude. We found 82KHZ is the best frequency to get many kinds of chaos which could observe the changing of chaos most clear.



C1 R(Ω) L(H)

R 215.96

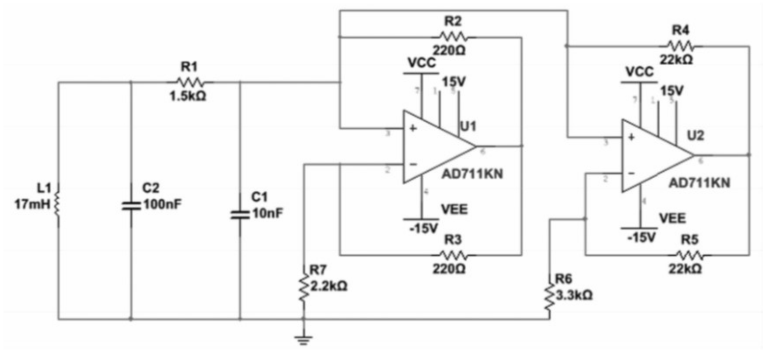
L	39.6(FD)|496(RD)	23.31
L	39.6(FD)|496(RD)	23.03

The best experiment results group:

U(V)	f(kHz)	ring number
1.6	82	1
2.4	82	2
2.8	82	3
3.3	82	2
5.4	82	4
6	82	inf
6.1	82	inf
6.5	82	4
6.6-7.6	82	inf
7.7	82	3
10.1	82	6
10.8	82	inf
12.1	82	inf
17.8	82	4
20	82	4-tend to inf

After that we try to find a solution to synchronize two same chaos circuit so that the pair of circuit could be used as encryption and decryption. But we didn't finish that this week.

The following circuit is also tested this week:



But we didn't have AD711KN, so we tried LF353 but the circuit doesn't work properly as conjecture.

Problem, issues and concerns:

The pspice simulation of same value of the real circuit cannot get same simulation results. The Chua's circuit with two AMP doesn't showed chaos yet.

Tasks for next week/Actions for next meeting:

Search for usage

encryption

Synchronize

More clear experiment results with a form

EXP SIMU

The Chua's circuit with two AMP

changeable C/L/R try different value and record

Supervisor use only

Progress Assessment: □ Satisfactory

Comments/Recommendations: Find out how op-amp circuit works. Try 'trimming' component values.

Supervisor Signature: SH

Supervisor weekly meeting log week 5

Date: 3/3/2019 Supervisor: Professor S. Hall

Project Title: Investigate a Chau chaos circuit (L, R, diode in series) – compare it to a linear L, C, R resonant circuit

Student Names /Attendees:	1.Yifan Wei	2.Tianjian Zhong
3.Lochlainn Hankin-Appleby		

Summary of weeks activities:

PSPICE simulations were carried out with the real values of components, in order to compare them to actual results. The simulations show 2 rings at 0.8V amplitude, and then going straight to chaos beyond this, whereas the real results do not get two rings until 2.4V, and go in steps of 2, 3 and 4 rings before devolving into chaos. We have FFT images of each of the attempted amplitudes, and can compare where there is bifurcation in the obtained frequencies.

We also did repeat readings of the RLC circuit with the new capacitance value, and it still gives only 1 ring no matter the voltage (as it should).

Problem, issues and concerns:

We are not 100% sure why we get these different results between sim and real, but we think it is due to floating capacitance in the circuit, as well as non-linearity and internal resistance in the inductor.

Tasks for next week/Actions for next meeting:

Bench inspection

Supervisor use only

Progress Assessment: □ Unsatisfactory □ Satisfactory □ Good

Comments/Recommendations:

Supervisor Signature:

Appendix B

Breakdown of individual contribution to the project

PSPICE simulations:

Lochlainn: 80%

Yifan: 10%

Tianjian: 10%

Experimental results/Circuit development:

Lochlainn: 10%

Yifan: 45%

Tianjian: 45%

Blog:

Lochlainn: 60%

Yifan: 20%

Tianjian: 20%

Poster:

Lochlainn: 20%

Yifan: 40%

Tianjian: 40%

Weekly meeting logs:

Lochlainn: 33%

Yifan: 33%

Tianjian: 33%

Project report:

Lochlainn: 80%

Yifan: 10%

Tianjian: 10%

Appendix C

Chaos oscilloscope X-Y figures

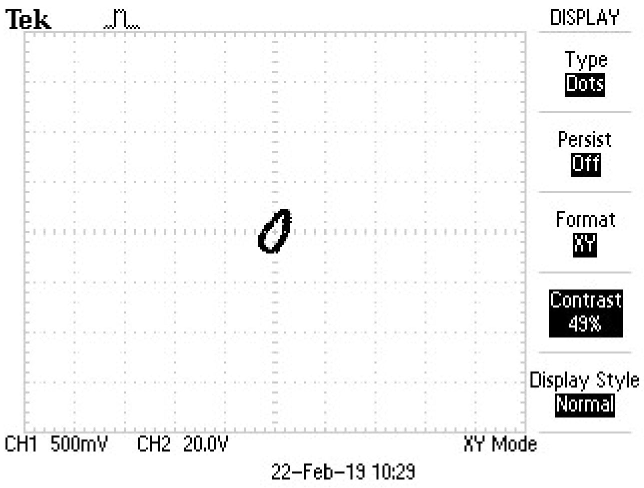


Figure C.1: Input 0.0V – 2.4V

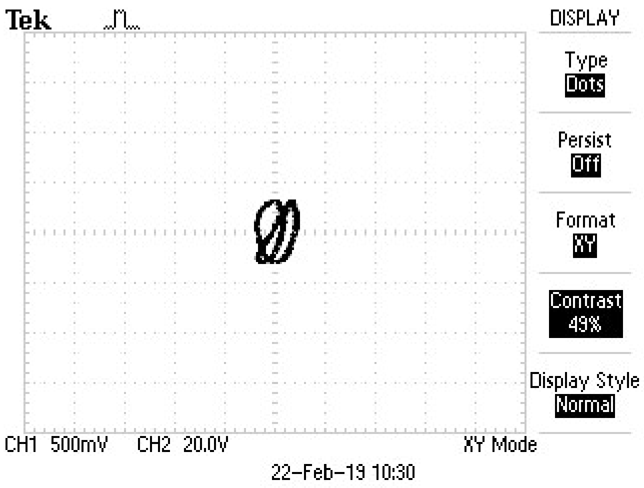


Figure C.2: Input 2.4 – 2.8V

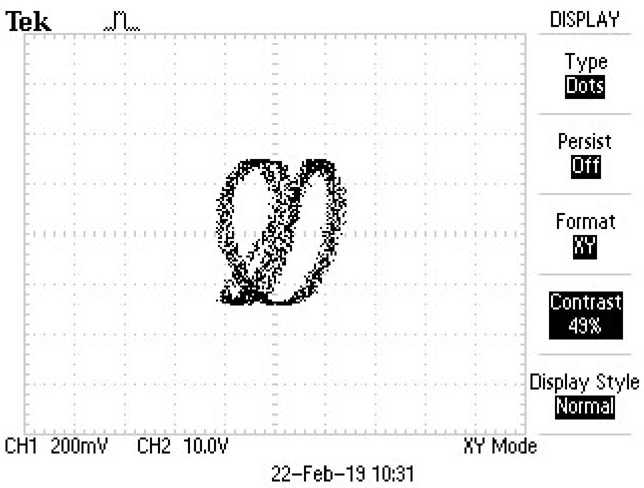


Figure C.3: Input 2.8 - 3.3V

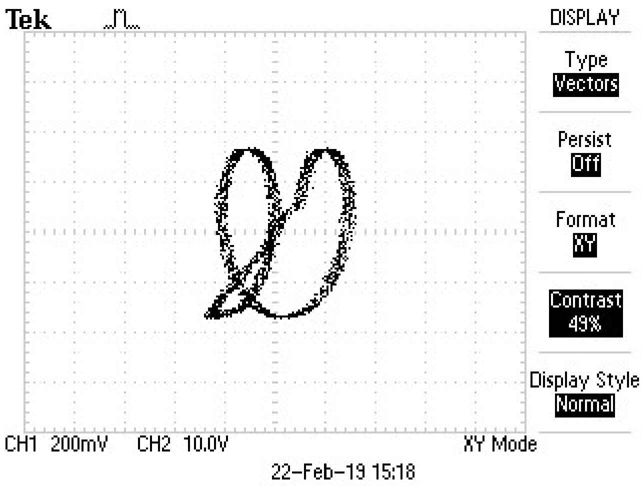


Figure C.4: Input 3.3 - 5.4V

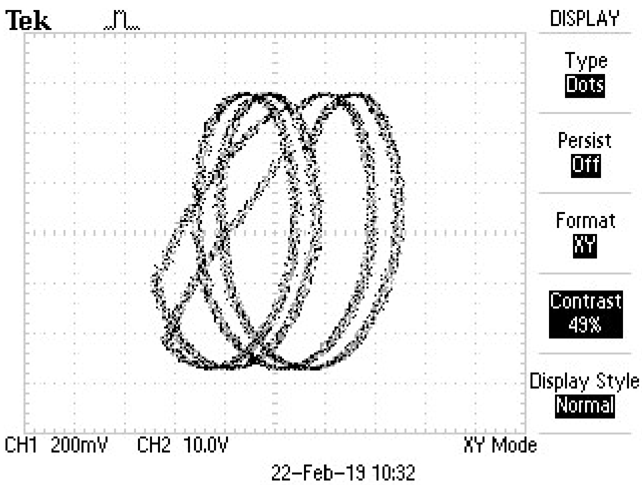


Figure C.5: Input 5.4 – 6.0V

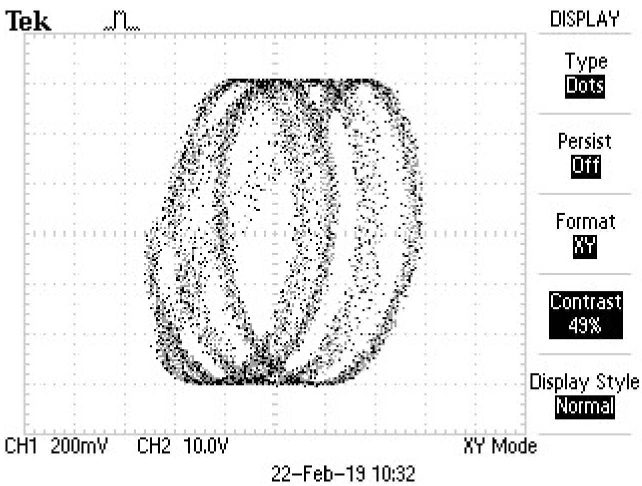


Figure C.6: Input 6.0 – 6.5V

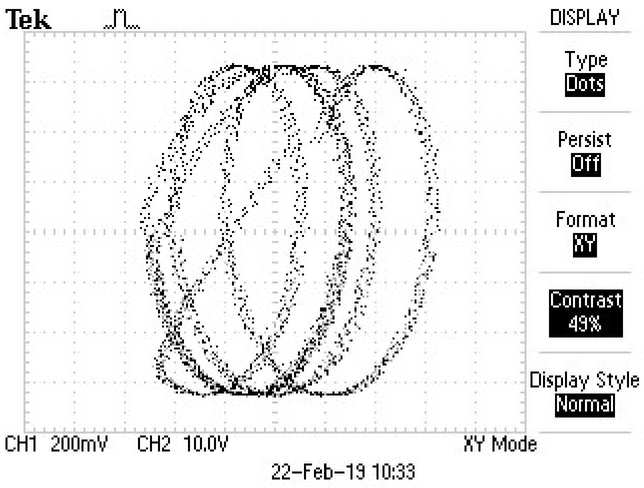


Figure C.7: Input 6.5 – 6.6V

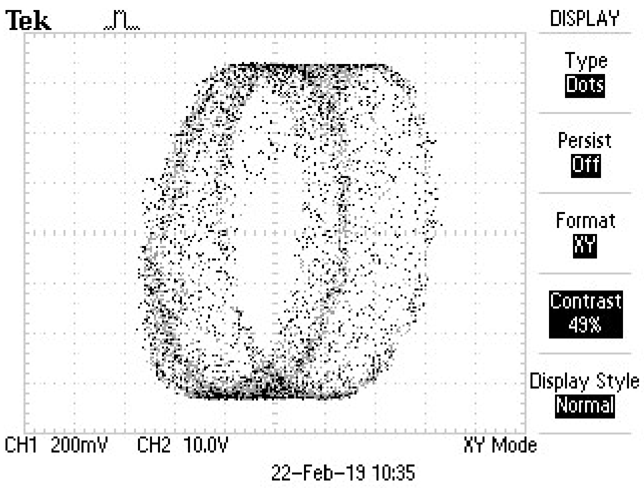


Figure C.8: Input 6.6 – 7.7V

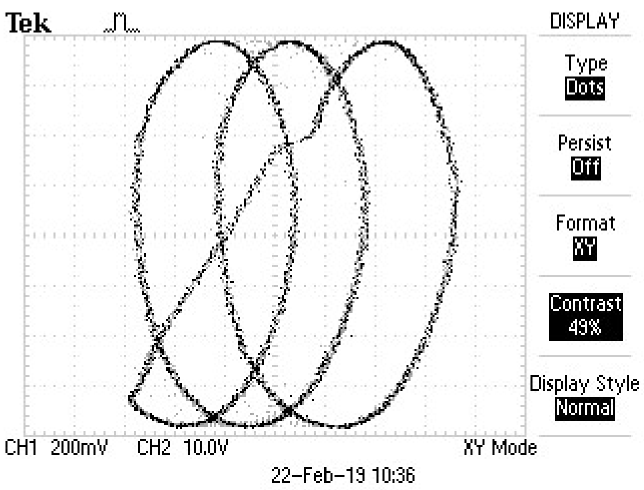


Figure C.9: Input 7.7 – 10.1V

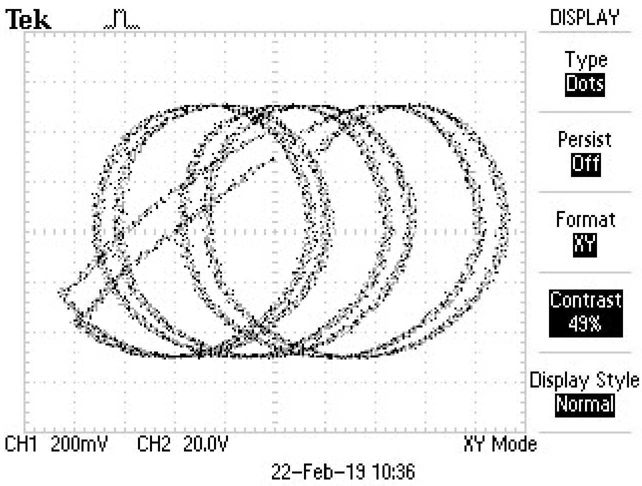


Figure C.10: 10.1 – 10.8V

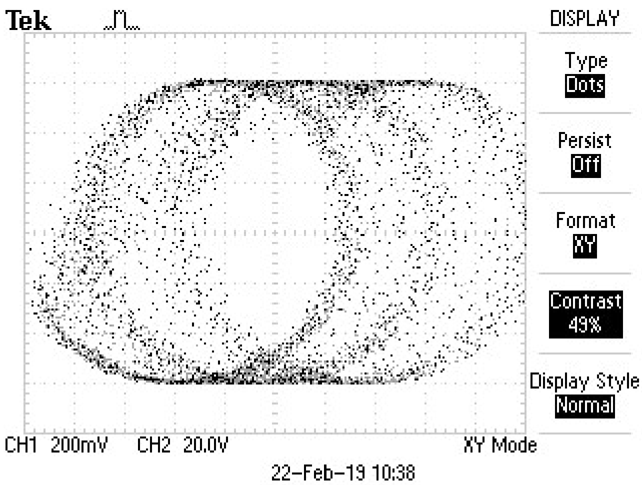


Figure C.11: 10.8 – 17.8V

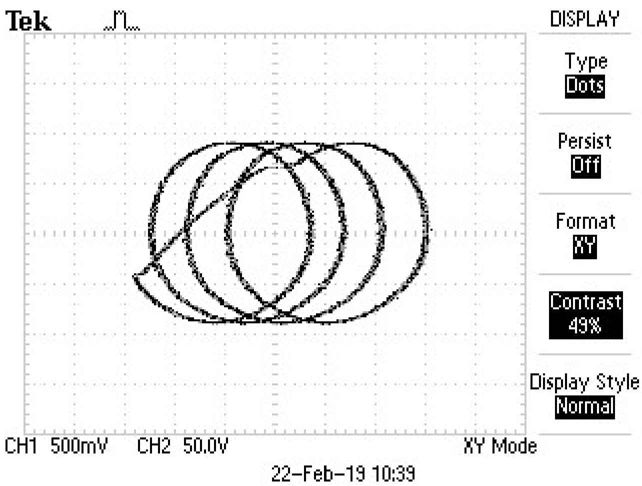


Figure C.12: 17.8 – 20V

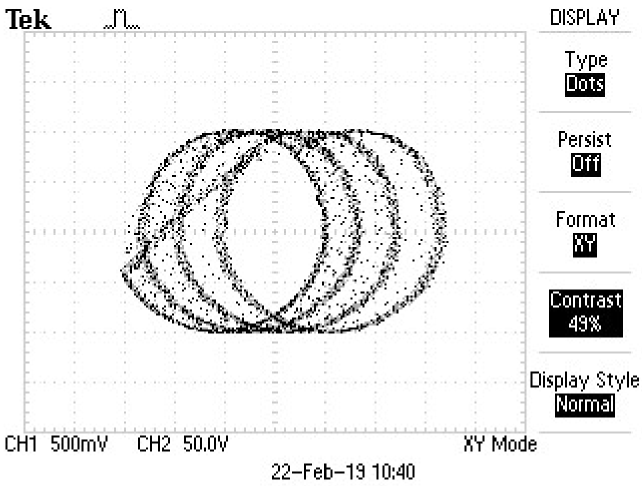


Figure C.13: 20V