Physics Experiments 1

Practicals manual

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Physics Experiments 1: Practical Manual
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Introduction

Fourier analysis is not just interesting from an analytical viewpoint. Fourier methods are so useful, that nearly every experiment performed at both LION & STRW incorporates some form of Fourier transformation. Every research group thinks in the frequency domain just as much as they think in the time domain. This is a very important skill to develop and practice.

Along with learning to perform frequency domain-experiments, we want you all to become better researchers. In a real laboratory, most researchers do not write down their results in large tables in lab journals. Instead, they use their computers to automate their measurements. It is time for you to learn that as well: PE1 will also be an introduction to performing automated measurements. For that extent, you will learn how to write `Python`-code to control the National Instruments MyDAQ.

Because both theory and practice go hand-in-hand, half of PE1 consists of practical sessions. The sessions follow the lectures closely. In the same order and just before each practical session the lectures will also treat the Fourier Transform, Bodeplots (magnitude and phase!), and applications thereof. In the practical sessions, you will learn how to apply the theory to make predictions for various electronic, mechanical and optical systems. This way, keeping up with the lectures and exercise classes will help you to understand the practicals and vice versa, the practicals will help you to understand the theory! Besides that, you will learn how to perform experiments in the frequency domain by making smart use of Fourier transforms and automized measurements.

PE1 will consist of six sessions. In the first one you will learn how to remotely control your experiment. During the second session you will learn to perform experiments in the frequency domain. In the third and fourth sessions you will respectively measure the magnitude and the phase transfer function of an RC-circuit. In these four sessions, we will give you very specific instructions. In the final two sessions, you will be given more freedom and you can choose from various applications of your newly acquired research skills. We hope that you will learn a lot and enjoy the PE1 practicals.

0.1 Learning Objectives

General learning objectives

During this course you get the chance to:

- learn how to think in a different domain than the time domain and will develop accompanying mathematical skills.
- develop Python skills that you can utilise again in all other courses.

Practical learning objectives

After successfully finalizing the practicals you will be able to:

- independently setup experiments to determine the transfer function of a linear system.

More precisely you will be able to:

- perform simple data acquisition by controlling a MyDAQ using Python.
- numerically calculate Fourier transforms using Python en interpret these Fourier transforms.
- numerically model and predict the behaviour of linear systems by making use of Fourier transforms and transfer functions.
- (optionally) create a simple graphical user interface (GUI) in Python.

0.2 Setup of the practicals

PE1 will consist of 6 sessions. Each session will make use of the theory that has been discussed in the lectures and exercise classes. Make sure that before preparing the practical, you are up-to-date on the exercise classes. These exercises provide you with the knowledge and skills required in subsequent practical sessions. A basic understanding of relevant theory is necessary, and is expanded on during the practical sessions. We think understanding the theory and applying it in practice goes hand-in-hand. This is backed by a strong correlation between exam and practical grade. We also think it's more fun this way.

The structure of the practicals of PE1 will be very similar to those of your first year practical courses EN1, EN3, and EN5. You will be provided with a short description of the experiment, including a research question. You will then perform the experiment in order to answer the research question, where we ask you to come up with your own research plan as much as can reasonably expected.

However, there are also some differences with the practicals you are used to. We ask you to keep these in mind. A large part of PE1 is about learning how to automate measurements using `Python` programming and modern equipment. You are familiar *using* such programs during EN, but now you will learn how to *write* such programs yourself. As you have not done this before, we will use the practical sessions to provide you with comprehensive instructions to develop these new skills in `Python` and lab work.

In order to teach you these new skills, you will be provided with `Python`-code and other digital material. You will read and analyze the given code in each session. After using the first part of the session to prove that your program is working as it should, you will proceed with the practical as normal.

We aim to give you choices in the type of experiment to perform during a session. Thus you need to indicate in your preparation which option of experiment you have chosen. When applicable there will be a Google form which you need to fill out as well. You only need to prepare the experiments that are part of your chosen option.

You write a preparation in order to smoothly and safely execute your experiment during the available lab time. Some of this preparation will take place at home, some of it will take place in the lab. While performing the experiment (also during the programming sections), you will keep a lab journal where you record your actions towards answering your research question.

You will perform each experiment as a duo. We do encourage discussing your hypotheses or results with fellow students and with the TA's! Experimental research is never a solo-act, and discussing ideas or interpretations is part of being a researcher!

The first five sessions of PE1 are formative sessions: your preparations will be graded but your lab journal will not: it will only be given feedback halfway through each session (ask for feedback whenever you like, even when preparing). During these sessions you will learn the skills and theory you need to successfully perform experiments in the frequency domain using automated measurements.

Preparing an experiment will take quite some time: please plan it accordingly and put in the effort that we expect. It will take you more that just an hour and visitng the practicals unprepared really is a waste of time. You will be able to pay more attention to details during the experiments when you are well prepared!

During the fifth session, you will perform 2 short experiments. During the sixth session, you will perform 1 long experiments in order to demonstrate your acquired skills. While you will keep a proper lab journal during all these sessions (we will check!), only the lab journal of the last session will be graded.

The rubrics that we will use to grade your preparations and lab journals can be found on BrightSpace and reflect the general learning objectives of practicals.

0.3 Lab Journals

Lab journals are essential for the documentation of scientific results and research. In your first year, you already learned how to keep a lab journal. Here, we only lead you through the basic aspects. We reiterate the goals of a good lab journal:

(a) A lab journal must be readable and understandable for a third party. Someone else must be able to use your lab journal to reconstruct your actions in the laboratory. Even if they do not possess the manual of the experiment! This ensures your experiment is reproducible, and therefore proper science! *In the meantime it also gives us the opportunity to get insight into your learning process and the problems you face.*
(b) A lab journal helps you to perform your experiments in a structured manner, and to work efficiently.
(c) It allows you to retrace your steps in the future, and thus helps you to construct new, effective steps when you get stuck.
(d) It gives you a place to record your smart ideas and insights.
(e) It is one of the documents that helps to guarantee lab safety.

To fulfill all these goals, you will be following an analytic pattern of reasoning and experimentation. By following this pattern, you will be able to efficiently draw new insightful conclusions from an experiment, and easily report your findings in papers, posters and presentations; even when you need the information from your lab journal many months after you performed the experiment. Note how nearly all these instructions have been taken directly from the first year's syllabus.

While writing your lab journal, you should use the structure from the following flowchart:

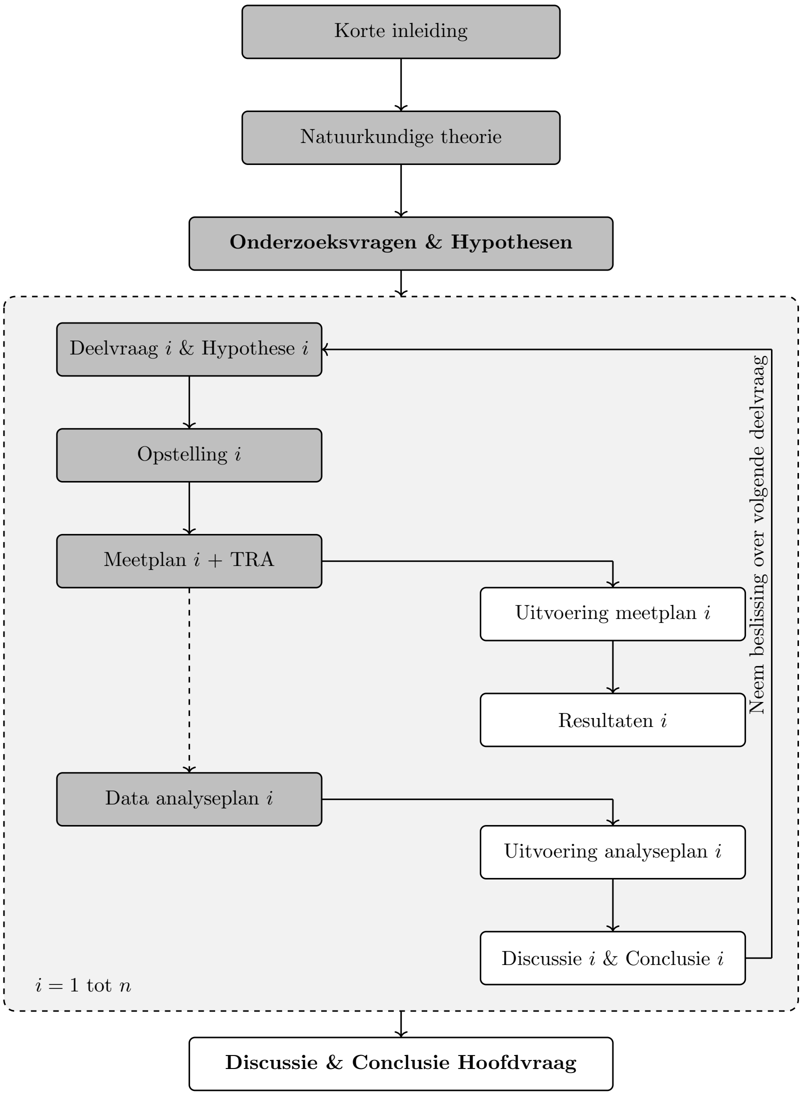


Figure 0.1 – *The (mandatory) structure of a good lab journal. Headings in dark grey are written as preparation before a session; headings in white are written in the laboratory. The headings as well as the research cycle (light grey) must be put into your lab journal* ***explicitly!*** *Use e.g. large, pronounced headers to implement this structure. Of course, you are allowed to add research questions whenever your research calls for them!*

In order to gain time and work efficiently you will **prepare** *all* dark grey steps before the session. Your analysis plan is an essential part of these seven steps. Writing a preparation ensures that even if something goes wrong or if something unexpected happens:

1 you understand the relevant theory
2 come up with hypotheses to test
3 execute a thought-out measurement plan
4 analyse your data properly
5 are able to answer any (sub)-research questions

Before starting the practical session make sure that before each session you have handed in your preparation as a pdf-file in BrightSpace. Also make sure that your lab journal is properly set-up in a collaboration space of your choice and send us a direct link to it. At the end of the last session for PE1 you will hand in all your lab journals as a pdf-file in BrightSpace.

To conclude this section, we now give a quick overview of each step in the lab journal and the information we expect to find within:

Personal details

We expect to see your student numbers and names, the name of your group, the date of execution, the name of the experiment and the name of the teacher. You can add more info if you like.

Short Introduction

A short introduction should be clear and concise. It really only takes three sentences: one sentence to provide societal context; one sentence to provide scientific context; one sentence to clearly formulate your scientific goal. Do note that we want to read the goal of your research, not the goal of the course! Anything longer than this takes away from the clarity of your message.

Physical theory

Here you summarize all the physical theory of your experiment: important theories and experiments in your field of research, that are **directly** applicable to your research. You only need to show a derivation if one of the steps in the derivation has fundamental importance to your research. In principle, analysis theory does not need to enter this section. However, if you are researching an analysis method, this would be a natural place to summarize the underlying theory.

Research Questions & Hypotheses

Formulate in a single sentence as concisely as possible the research question of the experiment. The research question should be as clear and scientific as possible. Write the answer that you expect: your hypothesis. A good hypothesis is always falsifiable and based on theory: it can be disproven which may have consequences for either your setup or the theory! Do not forget to give your hypothesis an error margin: when do you prove your hypothesis wrong? Each hypothesis need not be restricted to one sentence and may be as extensive as possible.

When your research question is very large, it becomes a *main research question*. You then ask *small research questions* in order to answer the main query. We ask that you present your small research questions and their hypotheses **in between** the main research question and its hypothesis. Every research question in your lab journal, no matter how big or small, is subject to the same scientific scrutiny: keep your work falsifiable! Your main hypothesis should be based on and consistent with your sub hypotheses!

Experimental Setup

Here you show and explain the experimental setup you plan to use. Be specific: another researcher repeating your experiment should use exactly the same setup *and materials* as you have! For example: make note of any specific dimensions of used materials or write down the type-number of used components or devices. If you re-use the experimental setup of a previous experiment, do not remove this header, but instead explain if, and what kind of modifications you have made.

Every heading should have a text where you explain what you are doing. Here, we also want you to make your plan visual: make sure to provide a structured, well-labeled and properly captioned sketch or schematic of your setup.

Measurement Plan

What if your hypothesis is false: how would you test it? What is the range within which you will say it agrees with the hypothesis and when do you reject the hypothesis? What methods would you use for this test? In the methods section, you describe your experimental test. Be as specific as possible, and do not forget to explain how you will collect and store your raw data. For example: how many data points will you collect? In what range? How long will each measurement take? Will you repeat measurements? What settings do you use when collecting data automatically (f.e. with a MyDAQ)? You can even put predictions of your raw data!

Experimental Execution (in the lab)

This section is written in the lab. Here, you must write down everything you do while performing your experiment. While you can and must refer to earlier sections, this is no excuse to simply write “I execute my plan!” No plan is ever planned and/or executed perfectly, and to ensure reproducibility, write down your process exactly. This especially includes all the things that go wrong, together with their solutions.

Make sure that you take note of which parameters you use in your measurement (e.g. temperature, voltage, frequency) and why you are stopping or continuing your measurements (e.g. noise below a threshold, weak signal).

Results (in the lab)

Here you show all your *raw* results including precision with which you were able to measure them. Raw data are results that have not yet been analyzed. Make sure to present it properly, preferably in graph-format but make sure to keep your raw data file. Make sure to plot correctly: for instance, we never want to see line plots anymore! If it is possible to generate raw data errors (and mostly it is), make sure to put error bars on your data points. Also, be sure to discuss any outliers or other interesting features of your data.

Data analysis plan

This plan should lead the reader from raw data to an answer to the research question. Be as precise as possible: which deliverable are you aiming to present, which raw data and formulas do you need for this, which function fit will you do and how do you judge the goodness-of-fit? The most important rule is: we want you to *explain* what you are doing. Preparing Python code at home is super smart, but does not replace an explanation! Always include error calculation (and error propagation) in this step and make this error propagation experiment-specific!

Analysis (in the lab)

Here you explain the execution of your analysis plan. You should be as exact and precise as you were in your experimental execution. Do not forget your error propagation! The steps you take in analyzing must be crystal clear. Be sure not to interpret your data yet; for now, you must remain completely objective and factual. Nobody should be able to argue with you about this section.

Discussion (in the lab)

In this section you interpret your data and your findings. Under ‘Results & Analysis’ you only present (analyzed) data. You use the ‘Discussion’ section to give it physical meaning. At the very least, compare your data to the hypothesis and discuss the size of your errors. Discuss the successes and shortcomings of your experiment and/or theoretical knowledge, and advise on future experiments.

Conclusion (in the lab)

Give the conclusions of your experiment concisely. Answer the research question, and repeat the most important findings.

Task-Risk Analysis

In the lab we have to perform several tasks that may include some non-trivial risks. Use the task risk analysis Excel sheet to summarize the possible risks during the practical and determine whether the suggested measures are sufficient. You can find this Excel sheet 'TRA' on BrightSpace together with several safety sheets. You can add it to the end of your preparation and your lab journal. Always update your task risk analysis to the current situation (e.g. the situation on covid is continuously changing).

Session 1: Remotely Controlling your Experiments

1.1 Introduction

In your first year in experimental physics, you have made measurements manually acquiring data and operating your setup, or used pre-made software to read data from the measurement equipment. For many experiments it would be more useful if you could control your setup and measure some quantity automatically. In PE1, you acquire these skills by applying them to the National Instruments MyDAQ, which is a device that can record and generate electrical signals. If you want you can buy a MyDAQ from us for use at home for EUR 100,-.

For this session, your goal is to learn how to read and write voltage signals using the MyDAQ. You will use Object Oriented programming [1] to create a python script that uses classes and functions to control the MyDAQ efficiently. Lastly, you will also investigate some problems which might occur when measuring automatically using the MyDAQ.

The research question you will answer will be **What is qualitatively the highest frequency you can observe with a given sample rate?** Before performing an experiment that answers this research question, you will learn how these measurements can be performed in the theory section. You will write and study this theory section in the lab and make a short assignment to apply it effectively: try not to use more than half your lab time for this purpose.

Be sure to have prepared your lab journal properly before starting this practical session.

[1] You will be writing your code using Object Oriented Programming (OOP) where appropriate. You should remember OOP from your first year programming methodologies course. If you are not that confident in applying OOP anymore, there is a Jupyter notebook on Brightspace and the T-disk to refresh your skills.

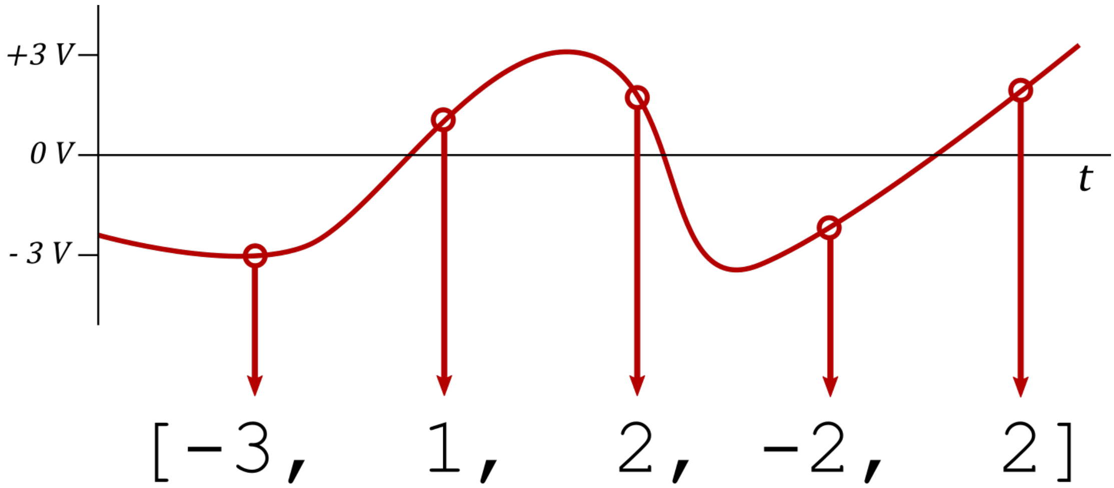


Figure 1.2 – *Schematic depiction of the process by which a MyDAQ converts an analog signal to a Python array.*

1.2 Theory

In this section you will learn how to read and write electrical signals with the MyDAQ. The MyDAQ can read and write voltage signals from and to multiple analog inputs and outputs. The MyDAQ has an input and output, and your system has an input and output. Generally, the output of the MyDAQ is connected to the input of your system, and the output of your system is connected to the input of the MyDAQ.

Your computer does not understand the concept of an analog signal: it only knows digital, discrete signals. In Python, voltage signals are therefore represented by arrays of voltages. You can see how a MyDAQ makes an array of voltages from an analog signal in figure 1.2.

A MyDAQ can record an analog signal: it then converts the signal to an array of voltages. But if you provide the MyDAQ with an array of voltages, it can also generate the corresponding signal!

When recording or generating an electrical signal, the MyDAQ writes the array's voltages sequentially with a certain *sample rate*. The MyDAQ's sample rate quantifies the amount of voltage levels read from or written to the MyDAQ per second. This sample rate can be freely modified, with a hard maximum of 200,000 samples per second.

Any conceivable signal can be generated by providing the MyDAQ with a sample rate, and an array of voltages. You could generate sine waves, square waves, Gaussians, or even write your own name on an oscilloscope. Be careful, however, that your signal is well-visible when using the chosen sample rate. If you have a sample rate of 1000 Hz, you cannot observe a signal with a frequency of 2 MHz for example (why not?). Related to this observation is the Nyquist-Shannon sampling theorem. You might want to look this up on Wikipedia, but we do not expect this from you at this point; it will be discussed in PE2.

It is now time for you to learn how to control the MyDAQ. On Brightspace and the T-disk, you will find the Jupyter notebook `PE1_Theory1_MyDAQ.ipynb`. This notebook provides comprehensive instructions on how to record and generate signals using the MyDAQ.

You will be applying your knowledge inside the practical, by programming code in Python scripts. You can use an editor of your choice; the PC's on the 3^{rd} floor have Spyder and Notepad++ installed. **Remember**: one of the objectives of this course is to learn how to automate your measurements. To train this, you will be writing stand-alone software: you should put all relevant code in a separate program. The Jupyter Notebooks should only be used for training!

1.3 Measuring

You could try to directly answer the main question, but this would be too much to ask. You should first set up a programming infrastructure, with reusable code so that the programming part of future practicals can be kept to a minimum. This section leads you through the steps you should take. Note that the research part starts here: at all times, stay scientific, keep a proper lab journal and critically test your research periodically through the use of smart research questions.

Writing to the MyDAQ

First of all, test whether you can successfully generate signals using the MyDAQ by writing an array of voltages to the device. Being a good researcher, you should check whether your program works by using an *Oscilloscope*.

Reading from the MyDAQ

Now test if you can successfully obtain input from the MyDAQ, by letting Python read the voltage array the MyDAQ records. Use a *function generator* to generate a known signal.

Make sure that you keep the signal below 10 V because the MyDAQ cannot handle higher voltages and will otherwise break!

Study the signal with an oscilloscope and measure it with the MyDAQ.

Note: Python has no notion of unit. Make sure you correctly translate whatever data you use to the correct units of voltage and time, that the MyDAQ expects.

Writing and Reading at the same time

Now write code that it is able to write a signal to the MyDAQ and read it back at the same time, correctly.

Finalizing your program

You should now have working Python code to record and generate electrical signals. Congratulations! The hard part is done. We can imagine that you would prefer not doing this again. Therefore, make a new Python script called `mydaq.py`. Organize your written code into a Python `class`, appropriately named `MyDAQ`.[2] You should design this class so that you can use it to read and write signals from and to the MyDAQ in the future. Make sure this class has the following functionality at minimum:

- The user can set a sample rate;
- The user can generate an arbitrary signal from an array of voltages;
- The user can generate a sine wave. The user should be able to choose the frequency, amplitude, phase-shift and offset;
- The user should be able to record voltage signals using the MyDAQ;
- The user should be able to obtain the time array corresponding to the recorded voltage array;
- Lastly, The user should be able to write to and read from the MyDAQ simultaneously.

If you feel like you need more functionality, you can always add it here. Where applicable, make sure that your program safely stores any measurement data.

You can write measurement data to a text file using `numpy.savetxt`, but you can also simply save a Numpy array to your disk using `numpy.save`.

It is important to keep in mind, that this is not some tedious programming task. You will actively use this self-designed class, not only to answer the research question, but also to perform experiments in all other five practical

[2]To use this class, you could type code in `mydaq.py` and run it. But you could also import the class into a separate file using `from mydaq import MyDAQ`, assuming both python scripts are located in the same directory.

sessions of PE1 (and even in sessions of PE2 and PE3). So it is wise to work hard on this class!

1.4 Answering the main research question

Finally, use your new class to investigate what frequencies of a signal you can qualitatively observe and distinguish at a certain sample rate. What are the advantages and disadvantages of using a MyDAQ instead of an oscilloscope or function generator?

Extra

Once you have answered the research question, there are some fun, optional applications you can investigate to see your class in action:

(a) You can investigate the following research question: **to what extent can the MyDAQ be used to control a servo motor**? You can later use this skill in PE3 for your own project. A servo motor comes with three leads: a black, red and white lead. Connect the black lead to ground, the red lead to +5V. You can use one of the blue +5V voltage supplies. Connect the white lead to the output (ao0) of the MyDAQ. The servo can be controlled by sending pulses to the servo. The high level of the pulses should be 5 V, the low level should be 0 V. The *width* of the pulses (in units of time!) tells the servo to which angle the servo should move. The pulses should be around 2 ms wide; changing the pulse width will change the orientation. Keep in mind that one pulse is not enough: you should send repeated pulses in order to move the MyDAQ! It is wise to send the pulses with approximately 50 ms delay.

(b) You can investigate the following research question: **to what extent can the MyDAQ be used to record audio signals using a BNC microphone**? A TA can provide you with a microphone and offer advise how to connect it.

(c) You can create a Graphical User Interface (GUI) for your MyDAQ! On Brightspace and the T-disk, there is a Jupyter Notebook on how to create a GUI with python. You can use this notebook to create a nice GUI for your MyDAQ program. While there is no main research question associated with a design task like this, being a researcher you should still use research questions to check your work!

1.5 Analysis

You do not have to analyse large sets of measurements for this practical. As always, you should think critically. Prove sufficiently that your code is working as it should: e.g. provide pictures of your input and output results and explain how you prove the required functionality. Combine as many observations as you can to come up with a critical answer to the research question. Naturally, after you are done, discuss and conclude in your lab journal.

1.6 Mandatory Preparation

Before starting the practical, you will prepare your lab journal. Already write down an introduction, theory, goal, research question(s) and matching hypotheses. Also write your measurement plans and analysis plans. We advice you to read up on Object Oriented Programming and look at the specification sheet of the MyDAQ. As always, we appreciate dividing your main research question into sub-questions, but due to the shortness of the practical, you do not need to use many, if any.

Session 2: Performing Experiments in the Frequency Domain

2.1 Introduction

When you read out a signal from a measurement, you are probably used to looking at the signal in it's time domain, where the magnitude is plotted against time. Complex systems or signals, however, are much more easily analysed in the frequency domain, which can be done by using a Fourier transform. Since our computers can only handle discrete sets of data, we will be looking at the discrete Fourier transform specifically.

For this session, your goal is to learn how to perform a discrete Fourier transform using python. Since a discrete Fourier transform returns complex numbers, you will also get used to using complex numbers in python. Finally, you will use the MyDAQ and the skills from the previous session to measure a signal and analyse it using the Fourier transform. In this session you will record audio of your own voice and try to record overtones of a PVC tube.

We have a limited amount of headsets (earphones + microphone) that you can borrow; these will not be cleaned in between sessions. It is better if you bring your own headset for this session (with microphone!), make sure it has a jack output; bluetooth or usb will not work.

The research question you will answer will be **is crucial information kept in the magnitude or the phase of the Fourier transform of different kinds of signals?** Before performing an experiment that answers this research question, you will learn how these measurements can be performed in the theory section. You will write and study this theory section in the lab: do not use more than half your lab time for this purpose.

2.2 Theory

In session 1 you learned how to send and record electrical signals using a MyDAQ and displayed/analysed these signals in the time domain. You wrote a Python class for this, that you should use today. Today you will learn how to display/analyse these signals in the frequency domain using a Fourier transform. Since a Fourier series is computationally intensive, we use a smart algorithm to compute it. This algorithm is called the fast Fourier transform (FFT). NumPy contains many smart and easy functions that can perform this FFT. On Brightspace and on the T-disk you will find the Jupyter notebook *PE1_Theory2_FFT.ipynb*, which explains how to use the FFT functions. To understand the Fourier transform even better you will learn (or have learned) during a computer practical how to code such a discrete Fourier transform yourself.

In Python the FFT function is expressed as an array with complex numbers; each complex number represents the Fourier coefficient at a frequency. Think about how the magnitude and phase information is represented in a complex number (e.g. think about the Euler representation of a complex number). To transform our signal back into the time domain we will use the inverse fast Fourier transform (iFFT) function. Be sure to look at the documentation of the functions you use.

Often, it is also important to display multiple orders of magnitude in a single graphic. This can be done by using logarithmic axes or by presenting your data in a Bode plot, which consists of both a Bode magnitude plot and Bode phase plot.

2.3 Measuring

This section leads you through the steps you should take. Note that the research part starts here: at all times, stay scientific, keep a proper lab journal and critically test your research periodically by posing smart research questions.

Record Audio using the MyDAQ

It is important that you can record and play back audio using the MyDAQ. To answer the research question, you will analyse audio signals. Your first steps in the lab should be focused on making sure that you can record audio using the MyDAQ. Since it is essential that this infrastructure works, you need to be very rigorous here: turn this into a proper research question[3] and

[3]'Can we ...' questions are almost always bad research questions, so avoid those!

critically test whether your setup works! Of course a proper test includes a setup description, hypothesis, measurement plan and analysis plan.

Setup

We want to record audio using your personal headset. The resulting signal will likely be very small, and thus needs to be amplified before we can measure it with the MyDAQ. In order to record audio using the MyDAQ, you need a microphone, a pre-amplifier, an oscilloscope and a BNC T-adapter. You can connect any microphone or headset to the input ("Mic IN") of the pre-amplifier using a 3.5mm to 6.3mm audio jack adapter[4]. Then you can use an audio-to-BNC adapter to connect the output ("CD OUT") of the pre-amplifier to the input port of the MyDAQ. Use your own python program (from the previous session) to record signals with the MyDAQ.

When working with audio always connect your signal to both the MyDAQ and the oscilloscope to avoid problems with incompatible input impedances (use a BNC T-adapter to 'split' your signal).[5]

Extra: On Brightspace and the T-disk, there is also a Jupyter notebook in which you can record audio from the audio jack in your computer/laptop. This is useful if you want to do these or similar experiments at home. For this session however, it is mandatory that you record audio using the MyDAQ.

Play back audio using the MyDAQ

To answer the research question, you should also be able to play back audio using a MyDAQ. To do this, you connect a BNC to banana-plug adapter to an output port of the MyDAQ. Then you can use a banana-plug to 3.5mm jack adapter to connect your headphones. You can now write out some audio signal to the MyDAQ and listen back to it using your headphones.

Experiments

In order to answer your research question, you should analyse different kinds of signals. Here we present multiple experiments you must perform, each with different kinds of signals, so that you can answer your research question. As a small bonus, you can use these experiments to become more familiar with Fourier transforms.

(a) **Information in voice recordings:** Record a couple of seconds of spoken text using the MyDAQ and perform the fast Fourier transform on

[4] If you don't know what an adapter looks like, you could use e.g. Google image search.

[5] We will discuss impedances more in PE2, but you could already look for more information online, e.g. Wikipedia.

this recording. We want to isolate the magnitude or phase information, to determine its importance; in other words: remove the phase or magnitude information. When uncertain, discuss different approaches to this problem with your colleagues.

   i) Perform a Fourier transform on your signal and isolate the magnitude information. Then perform an inverse Fourier transform [6] and listen back to the new, adjusted signal. What do you hear? What can you notice in the Fourier transform of the signal?
   ii) Now do the same, but isolate the phase information.
   iii) Finally remove and/or manipulate both the magnitude and phase together and see (hear) what happens.

(b) **Overtones of PVC-tube:** Record a couple of seconds of you blowing over a PVC tube, creating a nice sound. Use the FFT to measure the fundamental frequency and the overtones of the PVC tube. Also perform the same experiments as you did in **(a)** with this recording. First isolate the magnitude information, then phase information and lastly manipulate both and listen back to the recording. What do you hear this time?

(c) **EXTRA: Autotune**: You can use your skills with the Fourier transform to try and make a program which can tune your voice to a certain note or certain notes, or which can remove unwanted notes.

2.4 Analysis

As always, you should analyse your results critically. Reflect on your findings: do they (physically) make sense? If so/not: *why*?

For the measurement of the overtones, you need to acquire the frequencies of the peaks in the Fourier transform. You can use the function `scipy.find_peaks` [7] to find these peaks. Do you look at the magnitude or the phase information for this analysis? What is the accuracy of your findings? Compare your results with your theoretical predictions. Naturally, after you are done, discuss and conclude your main- or sub-research question in your lab journal.

[6] After performing an inverse FTT, make sure the magnitude of the new signal has the correct value such that you can listen back to it (see ipython notebook).

[7] look up the documentation of find_peaks online in order to vary the settings to find the best results.

2.5 Mandatory Preparation

Before starting the practical, you will prepare your lab journal. Like the previous session, already write down an introduction, theory, goal, research question(s) and matching hypotheses. Also write your measurement plans and analysis plans. We advice you to read up on the discrete Fourier transform and the overtones in a tube to make a (quantitative) theoretical prediction. Also make sure your python code for controlling the MyDAQ from the previous session works correctly. As always, we advice you to subdivide your main research question into several sub-questions.

Session 3: The RC-Magnitude Transfer Function

3.1 Introduction

In many experiments we are interested in the transfer function of our setup. This setup could be an electronic circuit, like a filter, but could also be a complicated electromechanical, biological, thermal or any other system. Systems that are present in all fields of experimental physics. The transfer function gives us information about the behaviour of our setup. Most importantly, it contains the system's response to various frequencies. Today, you will take the first step towards building a **spectrum analyzer** that can measure such transfer functions.

For now, your goal will be to investigate the magnitude part of the transfer function of a low-pass or a high-pass (RC-) filter using an automated measurement. In session 4, you will investigate the complete transfer function. Today, you will only investigate the magnitude of the transfer function. In other words, you will research what happens to the amplitude of sine waves as they pass through your filter.

The research question you will answer will be **what is the magnitude transfer function of my RC-filter measured through an automated measurement and how does it compare to my theoretical predictions?** Before performing an experiment that answers this research question, you will learn how these measurements can be performed in the theory section. You will write and study this theory section in the lab: do not use more than half your lab time for this purpose.

3.2 Theory

In session 1 you learned how to generate and record electrical signals using a MyDAQ. In session 2 you applied this knowledge to perform some short experiments with Fourier transforms. Today you will combine that knowledge to investigate the magnitude part of the transfer function of an electrical component using an automated measurement.

For this session you will build your own filter using a resistor and a capacitor: an RC-filter. In Chapter 1.4 of the reader for PE2 such a circuit is sketched and the transfer function is derived. Such a model of a circuit is not complete nor realistic however, as every electronic circuit contains several wires running parallel or crossing each-other at voltage differences. This results in an additional (frequency dependent) resistance in series and/or capacitance in parallel to the components (see Fig. 3.3). These are called parasitic resistance/capacitance, and are usually small. Be careful when designing your filter at choosing the resistance and capacitance of the resistor R and capacitor C, as at high frequencies the parasitic resistance or capacitance may dominate your circuit (and thus change its cut-off frequency).

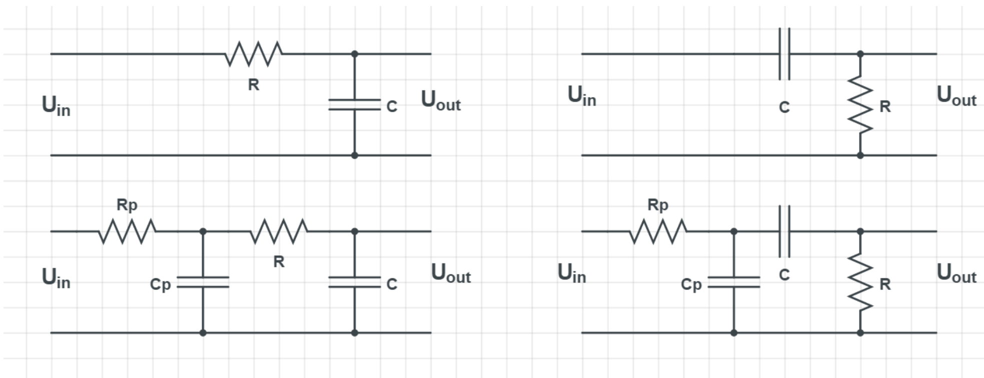


Figure 3.3 – *Schematic depiction of an RC-filter (left: lowpass, right: highpass). The lower figures contain a parasitic resistor (R_p) in series with the components and a parasitic capacitance (C_p) parallel to the components.*

The magnitude transfer function compares the amplitude of a signal after a filter, with its amplitude before the filter:

$$|H(\omega)| = \frac{|U_{out}(\omega)|}{|U_{in}(\omega)|} \tag{3.1}$$

You will extract this amplitude by making use of the discrete Fourier transform.

In a perfect world, the amplitude of the signal would be completely represented by one point on the Fourier transform. But measuring is never ideal, and the Fourier peak corresponding to your signal will take up multiple points in the transform.

So how do we compare the Fourier peak after the filter with the Fourier peak before the filter if we cannot simply use its height? Parseval's theorem tells us that the total *power* in (the sine wave component of) the signal is given by the integral over the power spectral density of your Fourier transformation. So instead of comparing the *height* of the peaks, you should be comparing the *power* of the peaks. [8]

If this still confuses you, do not worry. On Brightspace and the T-disk, you will find the Jupyter notebook *PE1_Theory3_Parseval.ipynb*. This notebook will explain you how to implement this in a Python program. You can test your skills by making the short exercise at the bottom of the notebook.

3.3 Measuring

Initial Measurements and Setup

You will now measure the magnitude transfer function of an RC-filter using an automated measurement. First build your RC-filter on a breadboard. Do not forget to make circuit diagrams in your preparation; you can choose resistors and capacitors from our supply. Try to design a filter such that you are able to easily measure its cut-off frequency with the MyDAQ (see Session 1). The supplies are identical to those you saw in your first year; we have resistors in the $10\,\Omega$-$1\,\mathrm{M}\Omega$ range and capacitors in the $10\,\mathrm{pF}$-$10\,\mathrm{nF}$ range.

You could immediately start measuring with the MyDAQ, but this is not a good idea. We should first get a general feeling of how this filter works, so that we can correct any mistakes we might make with the MyDAQ. So first of all, connect a function generator and an oscilloscope to the filter. Investigate the filter's magnitude transfer function qualitatively at various frequencies. What is the order of the cutoff frequency? Write down all useful findings in your lab journal; make sure you can draw a sketch of the magnitude Bode plot with all the relevant information.

Single measurements

Now you will measure the magnitude transfer function using the MyDAQ. To keep matters simple, we first measure the magnitude transfer function at a single frequency. Connect the output of your MyDAQ to the input of your filter, and the output of the filter to the input to the MyDAQ. Use your MyDAQ class to send a sine wave of a smartly-chosen frequency and amplitude from the MyDAQ to the filter. Simultaneously record the filter's response.

[8] Ask yourself: how does a ratio of powers relate to a ratio of amplitudes? In dB, the relation is especially simple.

If you are sure your program works correctly, use your knowledge of the theory section to let Python find the magnitude transfer function for you, automatically, *at this frequency*. How does the result compare to your measurements using oscilloscope and function generator?

Automated measurements

If you are completely sure your Python code works well (and have proven this), modify your Python code to subsequently perform this measurement at multiple frequencies. A possible strategy would be to make an array of frequencies that you want to investigate using `numpy.linspace` or `numpy.logspace` (which is smarter?). Then use your code for a single measurement in a for-loop for every frequency in the array!

Make sure your program safely stores your measurement data. You can write measurement data to a text file using `numpy.savetxt`, but you can also simply save a NumPy array to your disk using `numpy.save`. Now measure the magnitude transfer function of your RC-filter. Make sure to measure enough data points, at enough interesting frequencies!

3.4 Analysis

At this point, you should have measured the magnitude transfer function as a function of frequencies. In order to answer the research question, you will have to analyse the measured transfer function. What is the cut-off frequency and how does this compare to your theoretical predictions? Does the shape of the transfer function look similar to what you would expect? How steep is the slope?

Where possible, measure, calculate and propagate errors. You could use a function-fit (remember `scipy.optimize.curve_fit`) in order to compare your data to theoretical predictions. How large are your errors? Can they be lowered/removed? Naturally, after you are done, discuss and conclude in your lab journal.

3.5 Mandatory Preparation

Before starting the practical, you will prepare your lab journal. Already write down an introduction, goal, research question(s) and matching hypotheses. Also write your measurement and analysis plans per sub question. While you will write most of the theory section in the practical itself, you should prepare yourself to use **Parseval's theorem** and the theoretical predictions for an **RC-filter** (transfer function, circuit diagram) and already **choose the values**

for R and C that you want to use! Make sure you are able to elaborate your hypotheses by providing **a sketch of your predictions for the Bode Magnitude plot**. As always, we advice you to subdivide your main research question into several sub-questions.

Session 4: The RC-Transfer Function

4.1 Introduction

In many experiments we are interested in knowing the transfer function of electrical components in our setup. These could be simple filters, but also complicated electro-mechanical systems used in low-temperature physics. Today, you will finish building a spectrum analyzer that can measure such transfer functions.

For now, your goal will be to investigate the transfer function of the same RC-filter as last session using an automated measurement with the MyDAQ. In the last session, you only investigated the magnitude of this transfer function. Today, you will finish by measuring the complete complex transfer function: you will also research what happens to the phase of sine waves as they pass through your low-pass or high-pass filter.

The research question you will answer will be **what is the (complete) transfer function of my RC-filter acquired from automated measurements and how does this compare to my theoretical predictions?** After this session you are now able to make a complete Bode (magnitude and phase) plot, and thus also a polar plot of any (electrical) circuit. After three sessions, you have now learned everything we want you to learn with regards to the discrete Fourier transform and using the MyDAQ. Therefore there will be **no more** theory component to perform in the lab; you can write your theory section at home like you are used to. This time it is extra important that you prepare your experiment properly! Make complete predictions of your Bode (magnitude and phase!) plot and the polar plot, characterized by the values of R and C that you use. Write your measurement and analysis plans as elaborately as possible.

4.2 Theory

In session 1 you learned how to send and record electrical signals using a MyDAQ. In session 2 you applied this knowledge to perform some short experiments with Fourier transforms. In session 3 you learned how to use Parseval's theorem and the discrete Fourier transform to compute the magnitude part of the transfer function. Today you will have to use your knowledge of the MyDAQ to investigate the phase part of the transfer function of an electrical circuit using an automated measurement.

The transfer function compares the amplitude and phase of a signal after a filter, with its amplitude and phase before the filter. Before starting this practical, you should refresh your knowledge: what do we mean when we talk about the *phase* of a signal? How do we measure the relative phase of two signals? How do we obtain the phase in a Discrete Fourier transform? Make sure you can form hypotheses to these questions and write measurement and analysis plans so that you are able to answer them.

Measurement instruments, no matter how expensive, do not work instantaneously. Because of this, there will *always* be a slight delay between the writing task and reading task of the MyDAQ (which you probably already could see in the previous sessions). This delay is more or less random, which means that the phase of a signal which respect to $t = 0$ is very ill-defined and meaningless.

4.3 Measuring

You will now measure the transfer function of an RC-filter using an automated measurement. First recreate your RC-filter on a breadboard and check if it is connected properly.

Then measure the phase difference between your input and output signals at a single frequency. Remember that the MyDAQ is able to record signals from multiple input channels simultaneously. You can use this to correctly measure the phase difference between the input and output of your circuit. Reflect on whether you expected the measured phase difference at that frequency.

Expand your program to measure the phase difference at several frequencies. Now you should be able to make a Bode phase plot. Finish this practical session by making a program that can automatically measure the total transfer function, and generate the Bode magnitude and Bode phase plot both. Now, you also have all the information to make a polar plot (this contains both the magnitude and phase information in one visual).

Your complete program is now a spectrum analyzer and should be ready to be applied to various systems.

At this point, you probably want to perform (a large part of) your analysis. But in doing your analysis, you might find problems with your spectrum analyzer. For instance, there might be crosstalk between the two input terminals of the MyDAQ, as the MyDAQ itself is not grounded properly. Solve this by connecting the output of the MyDAQ as well to an oscilloscope or a buffer: this properly grounds all your connections. The scope is properly grounded through the electrical grid. A buffer is usually used to amplify the current or stabilize the output voltage, as you will see in sessions 5&6 and during PE2.

We expect you to repeatedly rotate between methods, analysis and discussion in order to perfect your spectrum analyzer. If you notice improper behaviour when looking at your Bode plots: start with a new research question, hypothesis, measurement plan, analysis plan, discussion and conclusion! Finally you could add some user interaction (e.g. an input statement for the start and stop frequency) so that in the future, you never need to program your spectrum analyzer again! Do not think lightly of this: you will use your spectrum analyzer for all the practicals of session 5 and 6!

4.4 Analysis

At this point, you should have measured the transfer function as a function of frequencies. In order to answer the research question, you will have to analyse the measured transfer function. Are you able to determine the relevant properties of your transfer function (shape, cut-off frequency, slope) from just the phase difference? Is this the same as the one you determined by looking at the magnitude part of the transfer function in the previous session? Does it have the same precision? If not: think about what reasons there might be for this discrepancy.

Where possible, measure, calculate and propagate errors. It might be advisable to use a function-fit (remember `scipy.optimize.curve_fit`) in order to compare your magnitude and phase data to theoretical predictions. Think about what systematic errors we can expect (from our devices) and what other error sources there might be.

To finalize this session, we expect you to make a polar plot of your transfer function. Note how most research groups (polar plots are the natural graphs for many physical spectra in for instance ellipsometry) do a function-fit of a transfer function directly to the polar plot, which should pose to be a nice challenge for you to do.

Naturally, after you are done, discuss and conclude in your lab journal.

4.5 Mandatory Preparation

Before starting the practical, you will prepare your lab journal. Already write down an introduction, goal, research question(s) and matching hypotheses. Also write your theory, measurement plans and analysis plans. **This time the measurement and analysis plans are extra important, as it (completely) defines how you will run the experiment**, so take the extra time to do it properly. When you do so we expect you to finish everything within the allotted time. As always, we advice you to subdivide your main research question into several sub-questions.

Session 5 & 6: Fourier Experiments

During the final two sessions of PE1, you will choose 3 experiments to perform in our lab: two short experiments during session 5 and a longer, more precise and quantitative experiment during session 6. The short experiments will allow you to become more familiar with several applications of Fourier analysis and/or the spectrum analyzer. During the longer experiment you will explore and research the physical aspects of your experiment and the analysis of your results more thoroughly and precisely yet within a time frame of 4 hours. This means that from your lab journal for session 5 we will be able to determine whether you grasped the basics of the PE1 course. From your lab journal for session 6 we will be able to determine the depth of your knowledge and the speed in which you are able to apply it!

All experiments have interesting frequency domain components and for nearly all we will directly apply the spectrum analyzer you built in the previous sessions. You can choose experiments from the options below. More elaborate descriptions follow later in this document.

1 Optics: Fourier Optics (p35)
2 Electronics: Characterizing a black box filter (p37)
3 Acoustics: Quantum analog (p39)
4 Electronics: Electrical resonator circuit (p41)
5 Mechanics: Mechanical resonator (p42)
6 Your own experiment! (p45)

One of the objectives behind the choice of these experiments is that you start getting an idea of the wide applicability of your newly gained knowledge and to hand you some ideas for your own research project during PE3 in the next semester.

In the description of each experiment there is noted what you should finish for the short or long version of the experiment. Like before, you will write a preparation at home for each experiment. The better you prepare, the more time you will have to focus on the experiment: write your measurement and analysis plans as well as possible, so you don't have to figure everything out on the spot! Use correct scientific methods and keep a tidy lab journal: this time both your preparation and your lab journal will be graded!

At the end of the final session, you will need to hand in your lab journal and a Python program (file extension `.py`) that contains the complete code for your spectrum analyzer on Brightspace. No delays or extensions are possible. This will be a requirement for finishing the course. This also means that you will not have time to 'finish up at home'; so be sure to keep your lab journal *during* the experiment, and try to pose and answer as many (sub) research questions as you can during the session!

5.1 Experiment 1: Fourier Optics

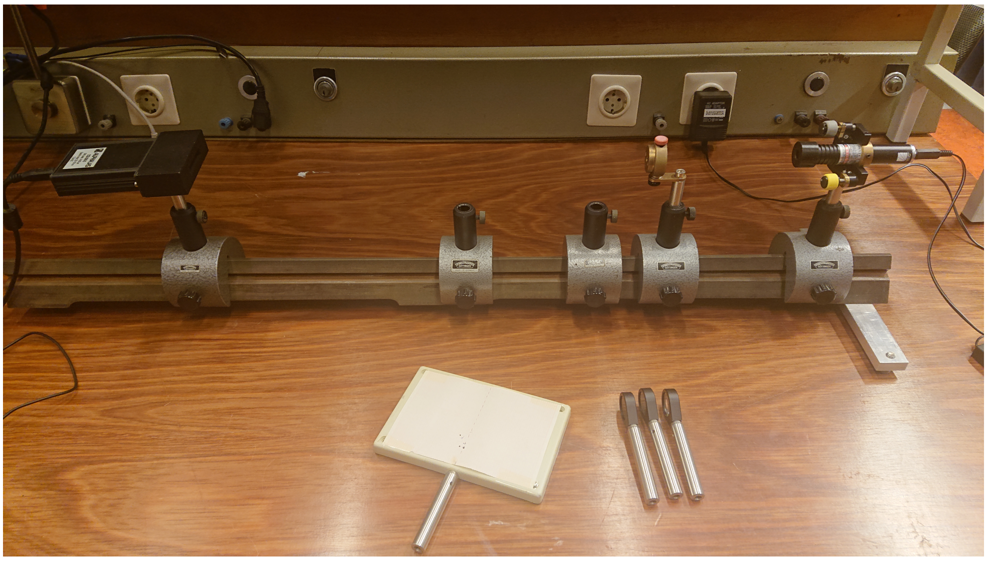


Figure 5.4 – *Picture of the single/double slit experiment. On the optic rail you can see (left to right): the Alphalas 2000-D one-dimensional CCD camera, 2 yet empty mounts, a mount to place the single or double slit, and lastly the laser. On the table you can see a screen, which you can use to align the optical setup, and 3 attenuators, to lower the power of the laser.*

In the optical lab we have set ups for single and double slits, in combination with a laser and a 1D Alphalas CCD. In this practical, you will record the diffraction patterns behind single and double slits.

Last year, most of you have missed out on this experiment during EN5 because you had to perform the experiment at home so here is an opportunity to perform the experiment with more precision and an extra analysis tool: Fourier analysis.

The research question will be: **to what extent do the predictions of Fourier optics describe the results of the single and double slit experiments in our lab?**

In the lecture, you have learned about the Fourier relationship between the shape of the slits and the diffraction pattern behind them. In your preparation, predict the diffraction pattern for each experiment. During the session, record the (intensity of the) diffraction pattern for each experiment. Take the inverse Fourier transform of the recorded diffraction pattern and describe what it means.

Note that the laser may be too powerful for the CCD; the sensor then saturates. You can (and should!) use attenuators to diminish the power of the laser. For safety never position yourself such that the laser is at eye-height. The laser we use has a UV filter and is generally safe to use. However: staring into the laser is still damaging; even looking at reflections may cause damage, so avoid looking at reflections when the laser is not attenuated.

When performing optical experiments, correctly aligning your setup is essential; make sure that every part of your setup is aligned! You can use the white screen to see the orientation of your laser beam at every point in your setup.

You can also change the width of the single slit, using the rotary adjuster[9] on its side. Describe qualitatively how the diffraction pattern changes when varying the width of the slit.

These are the mandatory measurements for the short experiment. We now continue with the more precise and quantitative part:

Note that we measure the *intensity* of the diffraction pattern. As such, we don't acquire a correct diffraction pattern when taking the inverse Fourier transform of our measurements. How should we analyse our data (intensity) to properly take the inverse Fourier transform so that we acquire the correct dimensions of the single/double slit? Try to base your analysis plan in theory.

You can also change the width of the single slit. Describe quantitatively (precisely) how the diffraction pattern changes when we vary the width of the slit.

[9]These knobs are really called adjusters! We checked...

5.2 Experiment 2: Characterizing a black-box filter

Figure 5.5 – *Picture of a "black box" that contains unknown filter #8.*

The research question will be: **what kind of filter does my black box contain, and what is (are) its characteristic frequency(ies) and its slope (order)?**

We will give you a box with an input and an output terminal. Inside this "black box" is a filter of an unknown type and order. What you do know about this filter, is that it can only contain passive electrical components: a resistor, inductor and/or capacitor. In this practical, you will recover the characteristics of the filter. In your preparation, summarize the known types of filters and the characteristics of their transfer function. Also describe the impact of the filter's order [10].

Write a measurement and analysis plan to acquire the relevant data and analyse it properly, such that you're able to answer the research question(s). Compare the magnitude and phase information to your theoretical predictions and describe what filter this is. Once you have optimised your spectrum analyzer this measurement can be done very quickly!

Note that you should always do a quick 'raw' check to see if your system is connected properly using an oscilloscope and function generator.

[10] See Reader PE1 Chapter 4.4, or subsequently Reader PE2 Chapter 1.4

These are the mandatory measurements for the short experiment. We now continue with the more precise and quantitative part:

What would happen when we connect an additional filter in series to our black box? Predict and describe how our 'total transfer function' changes. Connect your previously used RC-filter before or after the black box filter. Can you confirm or reject your predictions from your measurements and analysis? What is the difference between connecting your RC-filter before or after the black box?

Note: you can measure the resistance of the black box filter using a digital multi-meter (DMM) from the virtual bench, or ask a TA for one.

5.3 Experiment 3: Quantum Analog

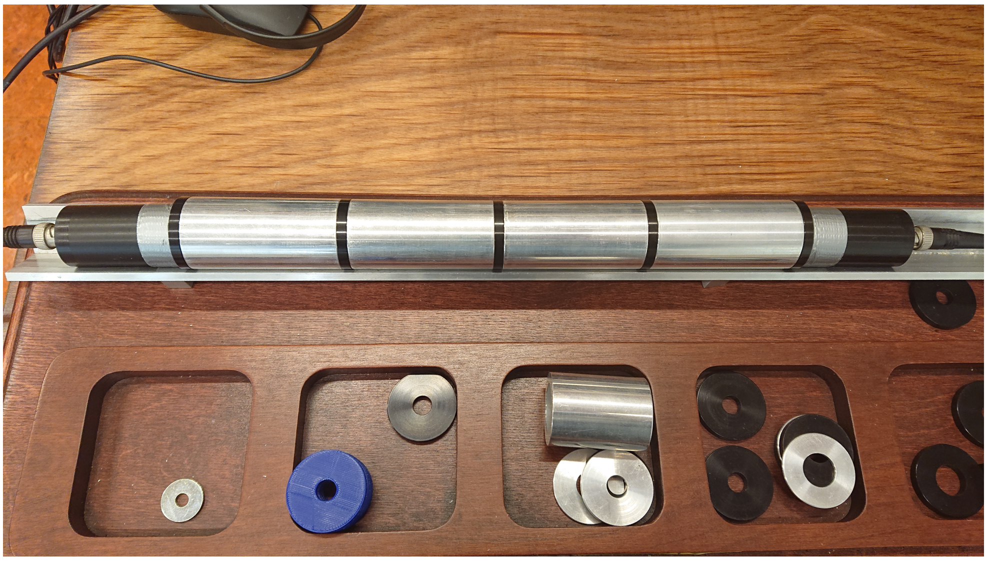


Figure 5.6 – *Picture of the 'quantum analog' set-up, consisting of equal length (aluminium) tube sections, separated by apertures (black disk with a small opening in the middle). A microphone and speaker are connected to the ends of the total tube.*

As a novel experiment, we have a set-up consisting of equally sized tubes, connected by disks with a small aperture. Sound can propagate from a loudspeaker through the tubes. At the other end, the wave amplitude can be directly measured using a microphone. A peculiar effect you will come across is that the transmission spectrum[11] depends on the amount of tubes that are connected, and on where you place the circular disks. This setup is used as a quantum analog when we compare this transmission spectrum to the energy of a particle in a potential well. The aperture of the circular disk is in this case analogous to the height (and width) of the potential barrier.

Sound waves will propagate through the tube sections and will reflect or transmit between each section. The amount of reflection/transmission depends on the frequency (and thus wavelength) of the incoming sound wave, and is also influenced by placing an aperture between tube sections. This causes certain frequencies to resonate in the tube sections.

Think about why the transmission/reflection of every sound wave is frequency (and wavelength) dependent, and also depends on the system properties (e.g. length of a tube). What happens at the aperture? What do you suppose is the difference between a setup with or without apertures in between tube sections?

[11] Transmission spectrum is another word for the transfer function in acoustic and optical systems like this.

Thus the research question will be: **how does the measured Fourier spectrum of the transfer function depend on the setup: the amount of tube sections and where the apertures are placed?** You only have 2 hours so limit your research. We expect you to at least look at the setups: 1. (1 or more) tube sections without apertures in between; 2. multiple tube sections with apertures in between; 3. a setup of your own design. Think about what would be interesting to change and what effect this should have on the transmission spectrum.

Note that you should always do a quick 'raw' check to see if your system is connected properly using an oscilloscope and function generator.

These are the mandatory measurements for the short experiment. We now continue with the more precise and quantitative part:

Find a quantifiable relation between the measured spectrum of the transfer function and the setup such that you can predict the spectrum of the transfer function of a (randomly) chosen setup. First try to verify simple models (look at setup 1. and 2.), and later find a relation that includes the effect of (not) separating tube sections by placing an aperture. Write in your measurement and analysis plans what setups will be interesting to look at and why. Try to discuss why this setup can describe quantum systems.

5.4 Experiment 4: Electrical resonator

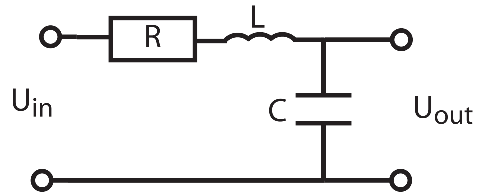


Figure 5.7 – *Schematic drawing of a LRC-circuit.*

Design an electrical resonator circuit using an inductor(L), resistor(R) and capacitor(C); such a system is also called an LRC-circuit[12]. Again: think about the proper values of L, R, and C such that you can correctly measure the behaviour of the system (in frequency space) using the MyDAQ. As mentioned in session 3, we have resistors in the 10 Ω-1 MΩ range and capacitors in the 10 pF-2.4 µF range. We have inductors with very high inductance: 1 mH-100 mH. As such, these inductors have a lot of copper inside them, and thus also have a high resistance ($10\,\Omega - 500\,\Omega$).

Measure the transfer function and make the Bode (magnitude and phase) plots and polar plot. Determine the resonance frequency of the system and its Q-factor.

The research question will be : **what is the resonance frequency and Q-factor of this electrical resonator, and with what accuracy am I able to determine it?**

Note that you should always do a quick 'raw' check to see if your system is connected properly using an oscilloscope and function generator.

These are the mandatory measurements for the short experiment. We now continue with the more precise and quantitative part:

Fit your predicted transfer function to your data in the Bode plot and/or the polar plot. Determine from this fit the resonance frequency and Q-factor and provide the error. How do your predictions and fit compare? Discuss your findings. Compare the accuracy when fitting in the Bode magnitude plot, Bode phase plot or polar plot. Are you also able to derive the Q factor from the width of the resonance peak? How does Q depend on the resistance of the filter?[13]

[12]see Reader PE1 Chapter 4.6 or check 'Collegeopgaves' 16-18.

[13]You can measure the resistance of the circuit using a digital multi-meter (DMM) from the virtual bench, or ask a TA for one.

5.5 Experiment 5: Mechanical Resonators

We have 3 types of mechanical resonator systems, which are driven in various ways (sketched in Figure 5.8):

A Ping-pong ball on a spring, driven by a loudspeaker
B U-tube containing water, driven by a vibration system
C Marble on a halfpipe (U-rail), driven by a vibration system

The transfer function of each system should have the shape of a resonating circuit. The research question will be : **what is the resonance frequency and Q-factor of one of these mechanical resonators, and with what accuracy am I able to determine it?**

As the resonance frequencies of these mechanical resonators tend to be very low (around 1 Hz), it may not be wise to take quick automated measurements using our spectrum analyzer. First use an oscilloscope and function generator to find the resonance frequency. Then measure at several frequencies very close around the resonance frequency[14] to sketch the Bode (magnitude and phase) plot. To discuss your results, make predictions for your Bode plots: define what the output and input of your system is, in order to define the transfer function. After this you can start using your python program to make automatic measurements using the MyDAQ. As we're measuring at low frequencies, your program might need some changes.

First note: you should always do a quick 'raw' check to see if your system is connected properly using an oscilloscope and function generator. Second note: a resonator will tend to move at its resonance frequency, so when measuring the transfer function make sure that the motion (output of the system) is in the same frequency as your driving force (input of the system).

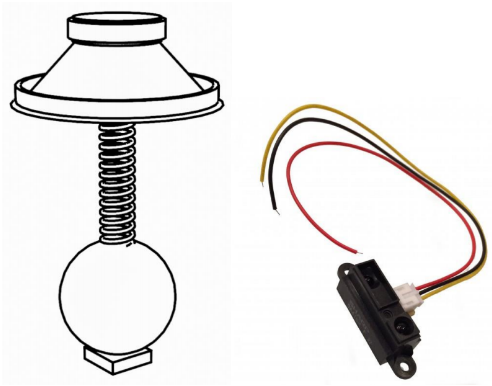
Measure the transfer function and make the Bode (magnitude and phase) plots and polar plot. Determine the resonance frequency of the system and its Q-factor. Try to optimize your setup and make sure to test your system (and sensor). Don't be too disappointed if you don't manage to generate nice plots, as we're trying to measure at very low frequencies and thus are sensitive to all kinds of noise.

These are the mandatory measurements for the short experiment. We now continue with the more precise and quantitative part:

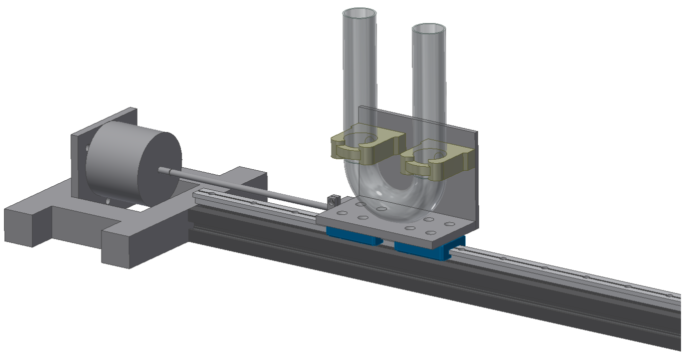
Fit your predicted transfer function to your data in the Bode plot and/or

[14]further than 1 Hz from the resonance frequency is not necessary

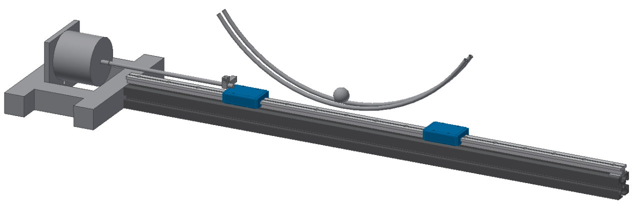
the polar plot. Determine from this fit the resonance frequency and Q-factor and provide the error. How do your predictions and fit compare? Discuss your findings. Compare the accuracy when fitting in the Bode magnitude plot, Bode phase plot or polar plot.
The Q-factor determines how quickly the system stops resonating after being driven. You can measure this decay in amplitude, and determine the Q-factor by fitting an exponential decay function (see PE2 Reader p75).



(a) *Left: schematic drawing of a mechanical resonator setup: ping pong ball on a spring, driven by a loudspeaker; right: infrared sensor that measures the distance to an object (ping pong ball).*



(b) *Schematic drawing of a mechanical resonator setup: U-tube containing a volume of water, driven by a vibration system. The oscillation of the volume of water is measured by water level sensors inside the tube.*



(c) *Schematic drawing of a mechanical resonator setup: marble on a u-rail, driven by vibration system; location of the marble can be measured by an infrared distance sensor.*

Figure 5.8 – *Schematic drawings of mechanical resonators.*

5.6 Experiment 6: Your Own Experiment

Naturally, if you can think of some setup or electronic circuit that you would like to analyze in the Fourier domain, you can do so! Your experiment has to be approved by one of us. If you are in doubt whether the experiment is doable in 2 or 4 hours, or if it has an appropriate level, ask a TA. Mail your research proposal (preparation + required materials) in advance to us: PE1@physics.leidenuniv.nl.

5.7 Mandatory Preparation

Before starting the practical, you will prepare your lab journal. Already write down an introduction, goal, research question(s) and matching hypotheses. Also write your theory, measurement plans and analysis plans. **This time the measurement and analysis plans are extra important, as it (completely) defines how you will run the experiment**, so take the extra time to do it properly. When you do so we expect you to finish everything within the allotted time. As always, we advice you to subdivide your main research question into several sub-questions.