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FPA course: Laser stabilization

Guidelines for students

In this experiment, the fundamental concepts of feedback and optimal control will be applied to stabilize the length of an optical resonator to the wavelength of a He-Ne laser. The feedback will be implemented by using a pre-configured FPGA board named Redpitaya programmed via Pyrpl. The FPGA will be used to characterize and monitor the error signal of a Pound–Drever–Hall (PDH) optical setup in order to control the position of one of the cavity mirror by a feedback loop. This experience can be combined with the "PDH stabilization" module as the second day of experiments. However, no prior knowledge of the PDH technique is required.

# Questions that will be asked before starting the experience. Unfortunately, it will not be possible to proceed if you do not know the answers!

* What is a dynamical linear system?
* What does “PI” mean? What is the meaning of “P”? What is the meaning of “I”?
* What is the “integral value” of a PI controller?
* What is the “set point” or “control signal” of a feedback loop?
* What are the Bode plots?
* Which are the stability conditions for feedback control?

# References

Main literature

* John Bechhoefer, “Feedback for physicists: A tutorial essay on control”, Rev. Mod. Phys. **77**, 783 (2005), <https://doi.org/10.1103/RevModPhys.77.783>

Additional literature and websites

* <https://www.redpitaya.com/>
* <https://pyrpl.readthedocs.io/en/latest/>
* Jingkun Guo, Richard Norte, and Simon Gröblacher, “Feedback Cooling of a Room Temperature Mechanical Oscillator close to its Motional Ground State”, Phys. Rev. Lett. **123**, 223602 (2019), <https://doi.org/10.1103/PhysRevLett.123.223602>
* B Abbott et. al., “Observation of a kilogram-scale oscillator near its quantum ground state”, New J. Phys. **11** 073032 (2009), <https://doi.org/10.1088/1367-2630/11/7/073032>

# Basic exercises

1. **Familiarize yourself with the system**

* Input a known function to the PI controller and monitor the output
  + Configure the “asgs” module of Pyrpl to output a wave.
  + Change each parameter of the PI controller (“pids” module) and check whether it happens what you expect.
  + Note that both the PI output and a waveform can be set together as a single output of the Redpitaya board. What happens in this case?

1. **Achieve first lock**

* Measure the error function of the system to characterize the linear region of the error signal.
* Determine the strength of the required feedback action assuming only a P feedback loop.
* Adapt P and I coefficients to lock

1. **Optimize the feedback**

* Measure the Bode plots with the “network analyzer” module
* What can you learn?
  + Are there mechanical resonances?
  + How do the Bode plots change if you alter P and I coefficients around your set values?
* Should you apply any filter?
* How can you optimize P and I coefficients?

1. **Feedback and measurement**

* Measure the feedback output and/or other signals.
  + Quantify how much the system is fluctuating around the set point.
  + Measure the maximum achievable resolution.

# Advanced exercises

Depending on the remaining time you can choose between

* Measurement of audio waves
* Program your own feedback control function
* Implement advanced locking strategies to cope with the non-linearites of the error signal

# Report

The target audience of the report should be other physicists who, however, are not familiar with this particular experiment. In the report, the discussion should flow from the beginning to the end by starting with an introduction, passing through the description of the experiment with the data analysis and finishing with a conclusion.

The introduction should contextualize your experiment/experience/findings from a broad perspective to engage your reader’s interest. It should start describing the general problem and narrow the subject down to prepare the reader to the next section, in which you describe the experience in details.

The descriptive part should contain an overview of the experimental setup. Furthermore, it should contain enough information to understand the data and the analysis. While describing every detail is not recommended, my suggestion is to structure the text in order to include a plot for each of the points (1), (2), (3) and, eventually, (4) described above.

The conclusion should summarize your findings and what you learned. In addition, it should broaden the discussion offering to the reader an outlook that emerges from your experience.

**Tips and tricks for the report**

* Take care of the first page/part. Include all the relevant information such as the date of the experience, the date you are handing in the report, a title, your names, your e-mails, the group number and the name of your supervisor.
* If you do not know how to “start writing” and find yourself in a “writing blockade”, I can suggest you to write an outline of the descriptive part and prepare the figures first. Then you may move to write the descriptive part, the introduction and the conclusion in this order. This strategy has worked for me because I familiarize with the problem by preparing and writing the central part. This allows me to understand the message I would like to give and, hence, design the introduction. The conclusions has often some symmetry with respect to the introduction, thus, I find it helpful to have the introduction already prepared.
* Plots without labels or with labels that are too small are not acceptable. My personal recommendation is, after preparing the report, print it and read the plots at the distance of about 1 m. The characters should be readable and there should be no label missing or wrong.
* Each figure must have a caption that describes the appearance of the content graphically. Further description and the meaning of what the figure presents may be written in the text. Every figure must be referenced in the text.
* The language style for writing physics documents prefers plain numbers over comparisons and superlatives. After writing your report, look for every “very”, “more”, “much less” … and complete or substitute them with quantitative measurements.
* Your opinions should be used to sustain the description of your experience and not to insinuate which are the reader’s ideas, background knowledge or general understanding of the subject. As for the previous point, while correcting your report, hunt down words like “easy”, “straightforward”, “obvious”, “difficult”, “simple” …
* You may use headings if you consider it appropriate, but avoid fragmenting the text by using too many of them. As a limit, I would suggest no more one heading per page.