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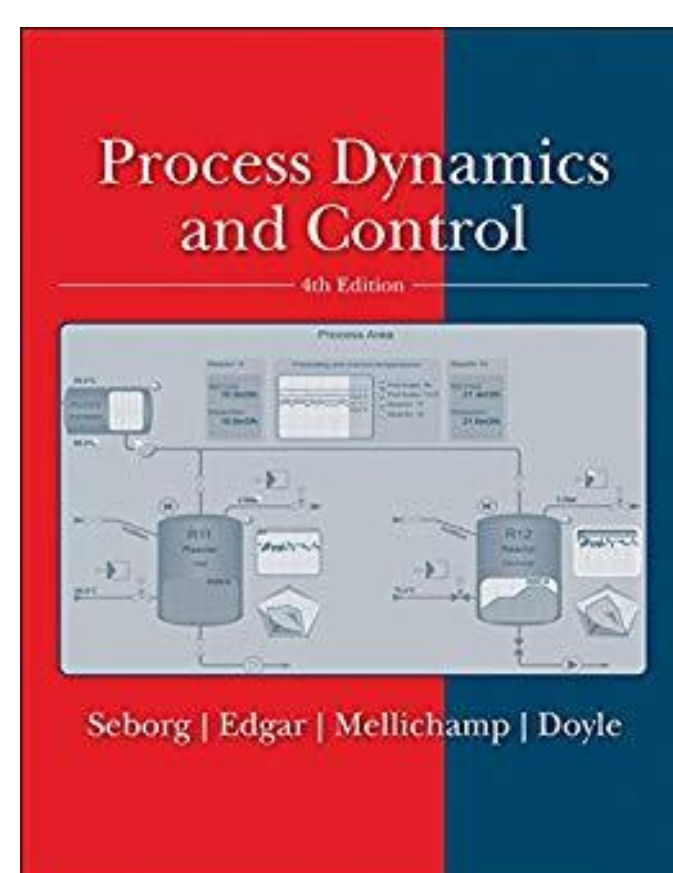
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What should Chem. Eng. undergraduate students learn about process control ?

We believe that the following concepts are key:

- The elements of a controller, the reasons for process control
- Why feedback and how to implement it
- **Performance vs stability trade-offs. How noise and time-delays limit performance**

Course: Introduction to Process Control, Fall '13
BSc Chemical & Bioengineering, Technical University of Denmark (5th or 7th semester)
~35 students, very diverse maths and computer programming skills
Main textbook: Seborg et al. (2011)



Is frequency analysis really necessary?

Yes! Frequency response analysis is a great tool for students to understand essential ideas about process control, such as:

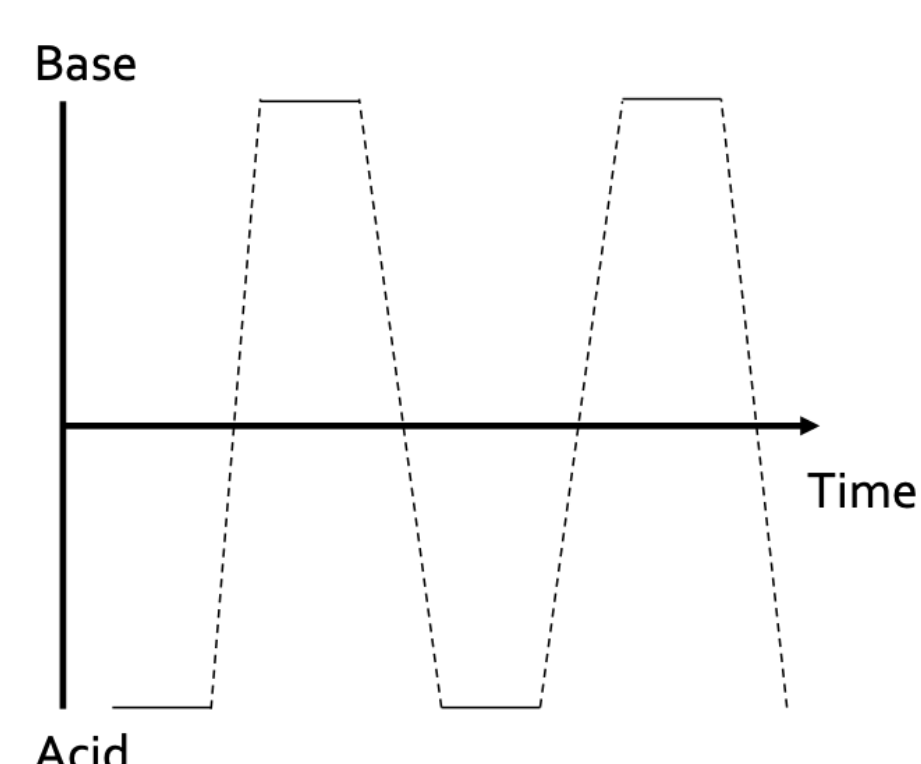
- The trade-off between controller performance and robustness.
- How a time-delay limits performance and stability

But frequency response analysis is difficult!

Not really, but it is unfamiliar for many Chem. Eng. students. It is not surprising as textbooks cover it as if meant for electrical engineers
That's why we have prepared the following experiment and more familiar examples related to Chemical Engineering

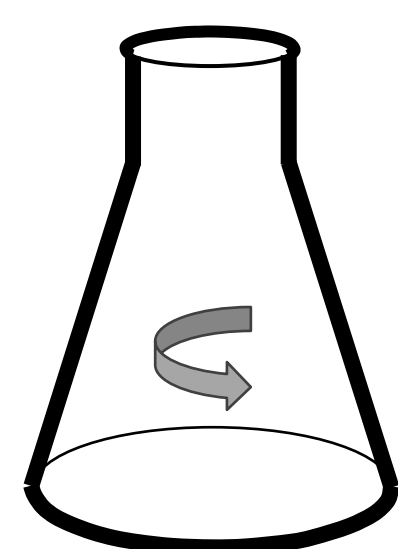
Understanding how the process gain changes with input frequency

- We prepared a colour change experiment and we made a video



Input: A quasi-sinusoidal addition of base and acid into an Erlenmeyer flask

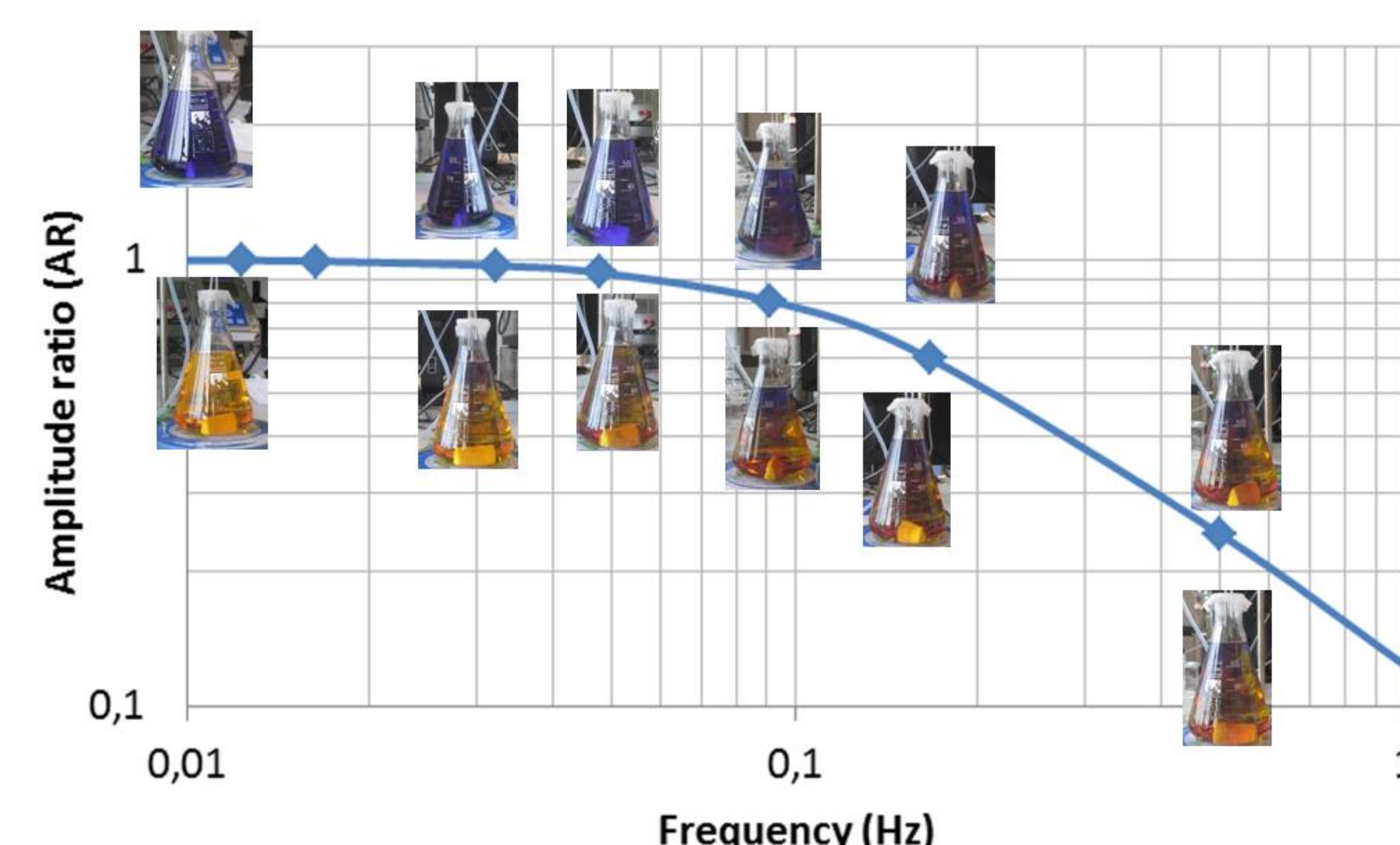
$$\frac{dC}{dt} = k_{mix}(C(t) - C_{\infty})$$



Slow stirring so that mixing, a 1st order process, is slow



If well mixed, blue thymol changes to blue at pH>8 and to yellow at pH<2



The gain of the process is the colour change. It decreases when we increase the frequency of the input

Understanding the meaning of the phase shift

- Seawater remains colder than air temperature during the spring; it is *delayed* with respect to the air temperature. The delay increases at increasing depths and can be estimated as

$$\theta = -\Delta\phi/2\pi v$$

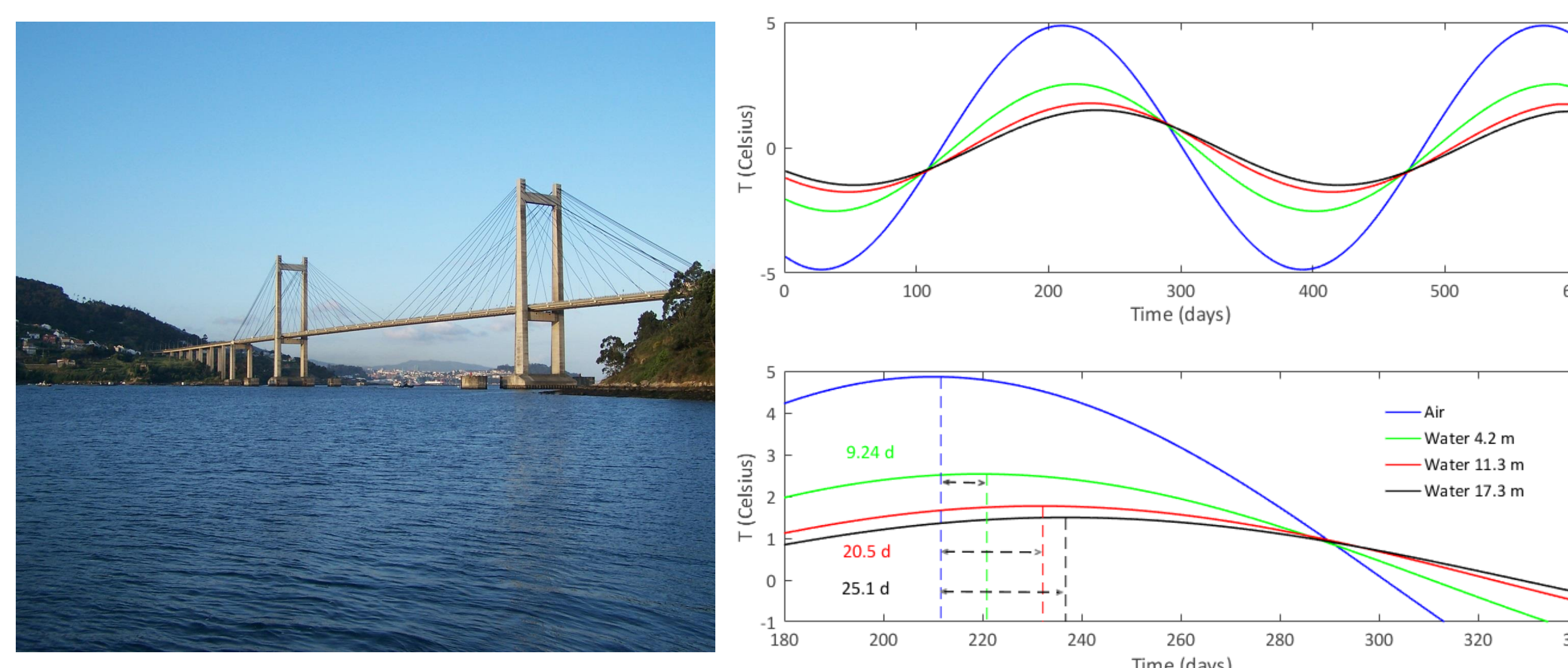


Figure 1. Temperature deviation from average in Rande bride (Vigo bay, left), along the year (top right) and magnification of summer maximum (bottom right). Data from Meteogalicia

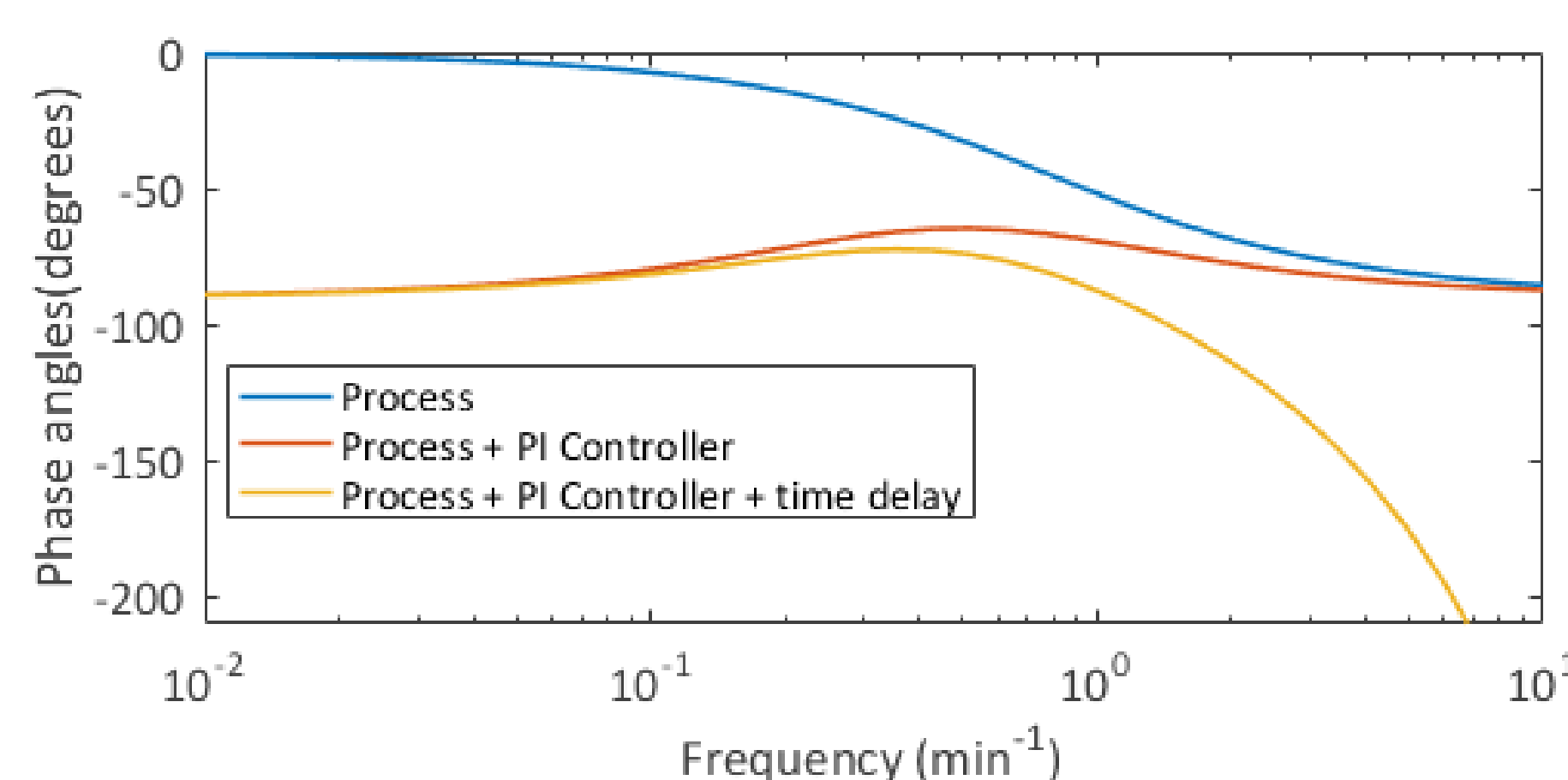
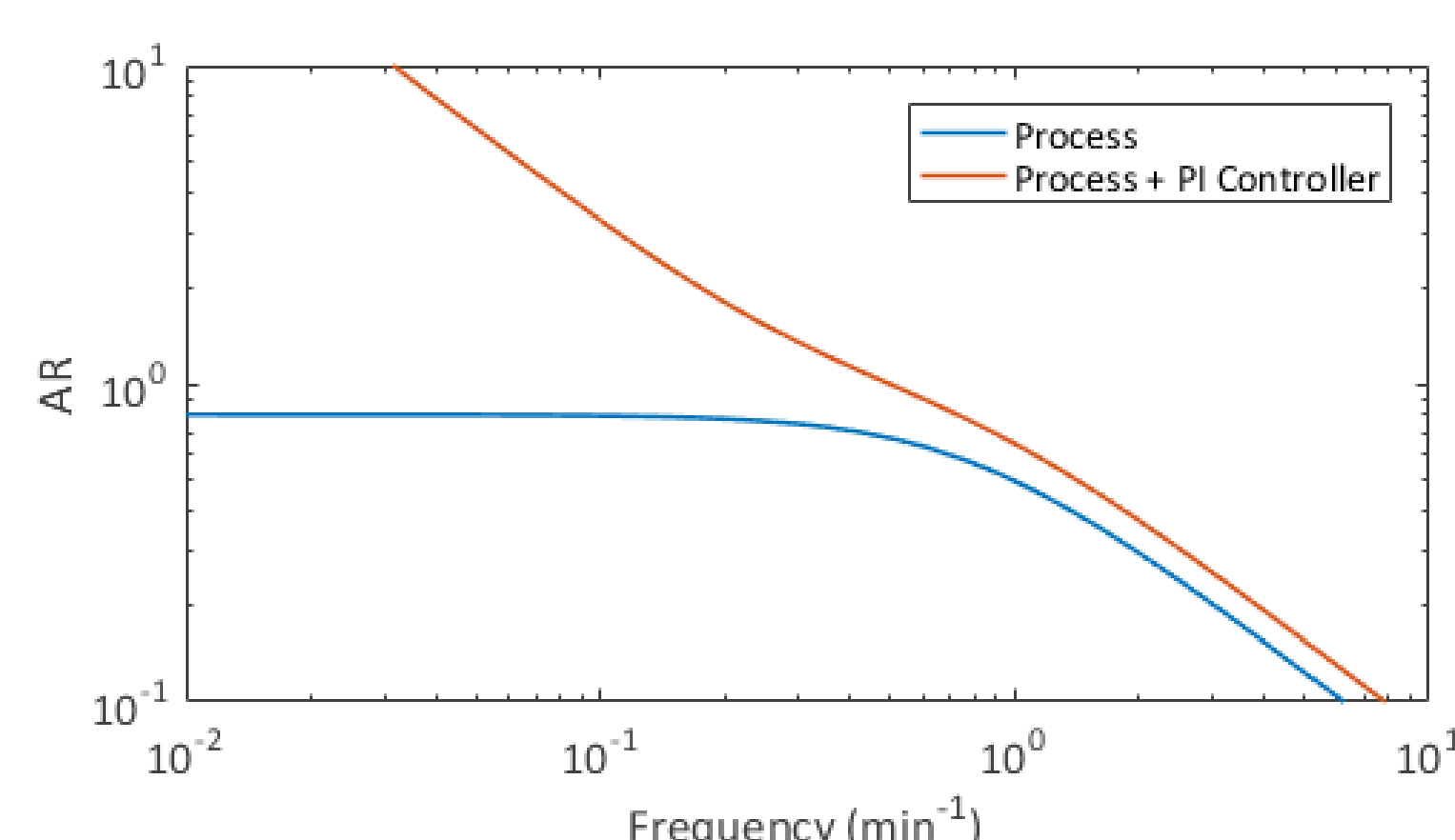
It is clear that the phase shift is equivalent to a delay

If the phase shift reaches -180°, the information is inverted

"The controller acts on the opposite of the deviation"

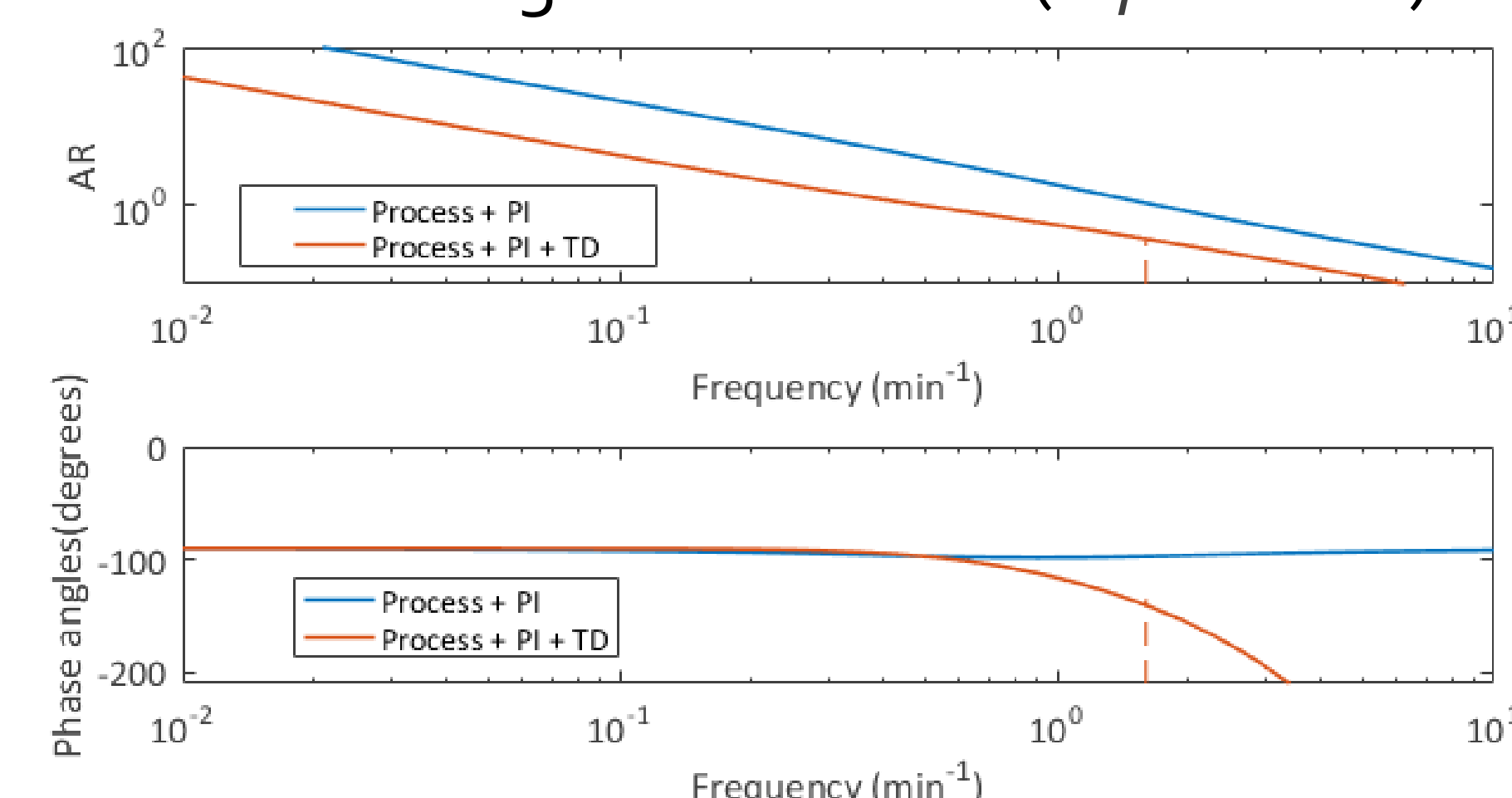
Gain, phase shift, stability and performance limits

- The gain tends to decrease with frequency, also for a controller



- The phase shift ends to become more negative with frequency. This trend is very strong for time delays

- For a process to be stable, it has to have a low gain (<1) when the signal is inverted ($\Delta\phi = -180^\circ$)



- A time delay decreases the $\Delta\phi$ a lot. Therefore a time delay limits the performance of the controller

